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DEVELOPMENT OF MAGNESIUM-CERIUM FORGED ALLOYS FOR ELEVATED-TEMPERATURE SERVICE

By K. Grube, R. Kaiser, L. W. Eastwood, C. M. Schwartz and H. C. Cross

Battelle Memorial Institute

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SUMMARY

The present report describes the results obtained in an investigation of magnesium-cerium forged alloys, which included (1) the development of improved alloys and (2) a fundamental study correlating alloy composition and structure with the resistance to creep.

The alloy-development phase of the project has been brought to a logical conclusion. The nominal composition of the recommended alloy is 1.7 percent manganese, 2 percent cerium, 0.25 percent nickel, and the balance magnesium. This alloy should be solution-heat-treated at 1040° F. In the experimental work, the alloys were heat-treated 24 hours at 1040° F, air-cooled, and then aged 16 hours at 400° F.

At 600° F this alloy has a yield strength and ultimate strength about 20 percent higher than those of EM22 alloy and time-deformation curves developed for these two alloys at 600° F and at 1300-, 2000-, and 2500-psi stresses indicate that the creep resistance of the recommended alloy is substantially better. Forging and hot-rolling tests indicate that the hot-working characteristics of the new alloy would be reasonably satisfactory but that it would be slightly more difficult to hot-work than EM22. No corrosion tests have been carried out.

Considerable progress was made on the correlation of composition and structure with the creep properties of the alloy. Although cerium is necessary to provide high tensile properties at 600° F, manganese appears to be the most useful in imparting high resistance to creep in the magnesium-cerium-manganese ternary alloys at 600° F. Only those alloy constituents which are or were in solution appear to be effective in improving the creep resistance of the material. It has been found that with 0 percent cerium good creep properties can be obtained only by quenching from the solution-heat-treating temperature, but with 2 percent cerium good creep resistance can be obtained by air-cooling from the heat-treating temperature.

Substantial differences in creep resistance have been produced as a result of differences in heat treatment, composition, and fabricating technique or as a result of uncontrolled differences from heat to heat of similar compositions and from specimen to specimen from the same heat of material. For the most part, metallographic examination at magnifications up to 500X does not reveal the structural differences which must necessarily account for such differences in creep resistance. The X-ray diffraction and electron-microscope examinations showed that the structure of the alloys is quite complex. In general, fine particles as revealed by diffused diffraction lines were generally associated with good creep resistance. Alpha and beta manganese, as well as one unknown constituent, were noted. There was some evidence that coarse particles of another phase, tentatively identified as the magnesium-cerium compound Mg_9Ce, had a slightly harmful effect on creep resistance. Preliminary results obtained with the electron microscope provided a fair correlation between the X-ray diffraction studies and the structure revealed at a magnification of 5000X.

INTRODUCTION

During the past 4 years, considerable work has been done on the improvement of the elevated-temperature properties of the magnesium-cerium alloys. Prior to 1945, little was known about the engineering properties of these alloys. It had been shown, particularly by the Germans, that these alloys appeared to have better elevated-temperature properties than those of magnesium-aluminum-zinc commercial compositions; however, quantitative data were meager. Some time later reference 1 was received from the Dow Chemical Company and proved to be of considerable assistance.

In 1945, a systematic investigation was begun under the sponsorship of the Air Materiel Command, Wright-Patterson Air Force Base, on magnesium-cerium-alloy development, one aim of which was to obtain data on the high-temperature properties of the 6-percent-cerium, magnesium-base (EM62) alloy. (See references 2 and 3.) As a basis for comparison, the commercial AZ63 alloy was tested with the magnesium-cerium alloy. Also, considerable information was obtained on the following:

(1) The use of zirconium as a grain refiner

(2) The effect of a fourth addition on the properties at room and elevated temperatures of magnesium-cerium-manganese casting alloys

(3) The relative effect of the grain size on the creep resistance

(4) The fatigue life of the EM62 and AZ63 alloys at elevated temperatures

At the conclusion of this investigation, the alloy-development phase indicated that the elevated-temperature properties could be improved by a small addition of a fourth element, but the experimental work was incomplete.

Since progress was being made on the development of casting alloys, another investigation was begun under the sponsorship of the Bureau of Aeronautics of the Navy Department to continue the alloy-development phase of the previous investigation, with particular emphasis being placed on the use of a short-time creep test as a means of screening out the best alloys. (See reference 4.) During the course of the alloy development, information was received from the Dow Chemical Company that the EM62 composition, now referred to as EM61, was difficult to cast into intricate shapes because of hot cracking attributed to the coarse grain of the alloy. Accordingly, the investigation was directed, in part, toward the attainment of a finer grain in the castings of the alloys. Previous data (reference 3) had indicated that zirconium was a potent grain refiner; however, its use in the melting room was cumbersome and the results were erratic. Therefore, since manganese coarsens the grain of magnesium-cerium-manganese alloys, steps were taken to reduce the amount of this element in the base composition.

When a fine-grained base of 6 percent cerium and approximately 0.80 percent manganese was employed, the emphasis of the alloy development was placed on obtaining good properties at elevated temperatures. As a result of this investigation, an alloy was developed, by adding 0.20 percent nickel and 0.02 percent tungsten to this base, which was fine-grained even at pouring temperatures of 1500° F and, therefore, may be less hot short than EM62 alloy. In addition, it had better tensile strength and yield strength at elevated temperatures. The creep resistance of this alloy tested at 600° F under a 2500-psi stress was markedly superior to that of E6 alloy and comparable with that of the EM62 alloy, although not quite so consistent. A comparison of its properties with those of E6 and EM62 alloys is presented in table 2 of reference 4.

Another investigation of forged alloys was instituted by the National Advisory Committee for Aeronautics. (See reference 5.) The objectives of this project were (1) to establish the optimum extrusion and heat-treating procedures for the alloys and (2) to improve the properties of the forging alloys by modifying the EM62 composition. The attainment of these two objectives was carried on simultaneously, employing the indirect extrusion press as a means of fabrication.

During the course of this work on forged alloys, data were obtained on (1) the effect of heat treatment and the degree of reduction by extrusion and (2) the effect of the addition of a fourth element to the EM62 base composition. At the conclusion of the investigation, the evaluation of the various alloys prepared was incomplete. However, a

single test indicated that 0.50 percent aluminum added to the EM62 base improved the creep resistance when tested at 600° F under a 1300-psi stress.

The present investigation was conducted at the Battelle Memorial Institute under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics. It consisted of two parts: The first part included the completion of the alloy-development investigation and the second part dealt with the fundamental study of the relationship of composition and structure to creep properties. The general purpose of the fundamental study was to learn what type of structure is necessary to produce good and consistent creep properties. Such information would be of considerable assistance in the development of alloys having good creep resistance. The fundamental study of the relationship of structure to creep properties included the following:

(1) The effects of fabricating procedure - casting, extruding, forging, and rolling

(2) The effect of cerium content on the tensile and creep properties of 1.7-percent-manganese alloys in the annealed, the heat-treated, aged, and stabilized, and the heat-treated, quenched, aged, and stabilized conditions

(3) The effect of manganese content on the tensile and creep properties of 2- and 4-percent-cerium alloys in the heat-treated, aged, and stabilized condition

(4) The effect of grain orientation on the creep properties of EM42 sheet

(5) The explanation of the cause of difference in creep resistance of materials having differences in composition, heat treatment, and fabricating history

(6) The cause of differences in creep of similar materials from two different heats or two different specimens from the same heat

GENERAL PROCEDURES

The general melting, casting, and testing procedures were similar to those used in former projects on magnesium-cerium alloy development and described in references 2 to 5. However, for the sake of completeness, much of this description is repeated in the following pages.

Melting Methods

The procedure used for the preparation of the magnesium-cerium melts consisted in melting the pure magnesium and/or the A.S.T.M. M1 alloy in the amounts required to produce the desired manganese analyses. These melts were made in a steel crucible. As soon as the charge was lowered sufficiently in the steel pot, a tight-fitting cover was placed over the crucible, and a protective atmosphere of nitrogen introduced. The melt temperature was raised to approximately 1400° F, at which time the cover was removed and the melt protected with Dow 181 dusting agent during the subsequent cerium (misch metal) addition. This operation also required thorough stirring of the melt, during which time the Dow 181 was used as a protective agent. The holding time of approximately 1 minute per pound of melt was employed after the stirring operation. This holding period was carried out while the melt was under the protective nitrogen atmosphere.

Elements of high solubility in magnesium were usually added along with the cerium, whereas those of low solubility or relatively high melting temperature were added to the magnesium prior to the cerium addition so that a higher temperature could be used. Nickel and a second element were usually added in the form of a nickel-rich alloy containing the second element. If the nature of the alloy addition required a high temperature, Dow 310 flux was employed as a protective agent up to the time of the cerium addition. After the alloy additions had been made and thoroughly stirred, the melt was held under a protective nitrogen atmosphere for the above-mentioned holding period to permit certain nonmetallics to settle.

After the settling period, the metal was poured into a preheated 4-inch cylindrical mold and, in some cases, also into a green-sand, four-bar mold. The ingot mold was preheated to a temperature equal to the pouring temperature of the metal. An interval of 2 minutes was employed to allow certain nonmetallic constituents in the melt to settle to the bottom of the ingot. The preheated mold with its contents was then cooled by introducing water into a surrounding container and permitting the water to rise slowly up over the outside walls of the ingot mold. During the solidification period, the ingot mold was vibrated continuously until the metal was completely solidified. This method of ingot casting produced directional solidification and provided an ingot free of pipe and other unsoundness.

In some cases, slabs for rolling were cast along with the billets for extrusion. These slabs were poured into two sizes, namely, 5 by 5 by $1\frac{1}{2}$ and 8 by 6 by 1 inches. To determine the forgeability of the alloy of optimum composition, ingots approximately 5 by 5 by 8 inches were cast into a gray-iron ingot mold fitted with a copper bottom. The mold was equipped with a refractory hot top to insure adequate feeding

of the ingot during solidification. The type of crystalline structure formed by this method of casting is more suitable for forging than that obtained in the cylindrical mold.

Fabrication Methods

A 250-ton press was available for the extrusion process. This was equipped with indirect extrusion tools for the purpose of extruding machined $3\frac{1}{16}$- inch-diameter billets to 3/4-inch-diameter bar stock.

The indirect extrusion method was chosen over the direct method because (1) lower maximum pressures are required, thereby permitting the use of a larger extrusion billet for a given press capacity, and (2) the extruded rod is reported to be more uniform from one end to the other because of the manner in which the metal flows from the container through the die.

When using the indirect extrusion method, the extrusion billet is placed in the preheated container, the die at the end of the ram moves downward, and the metal is extruded through the hollow ram up through the open top of the press.

A single-stand, 8-inch, experimental rolling mill was employed for rolling some of the experimental alloys. Frequent reheating and light reductions per pass were found to be prerequisites for the production of suitable sheet material.

Heat Treatment

The magnesium-cerium alloys were generally solution-heat-treated for 24 hours at 1040° F in an air-circulatory type of furnace. A small percentage of sulfur dioxide was maintained in the atmosphere throughout this cycle. Except where otherwise noted, the material was air-cooled from the solution temperature, after which it was aged 16 hours at 400° F. A stabilization treatment was employed for all specimens tested above 300° F. Those to be tested at 400° F were held 24 hours at 500° F, those to be tested at 500° F were held 24 hours at 575° F, and those to be tested at 600° F were held 24 hours at 650° F prior to testing. When an accelerated rate of cooling from the solution temperature was desired, cold water or oil was employed as the quenching medium.

High-Temperature Tensile Tests

Tensile tests were made at room temperature and 600° F on all of the extruded and forged material. To evaluate the alloy of optimum

composition, tests were made also at 300° , 400° , and 500° F. Briefly, the high-temperature tests consisted in placing a 0.505-inch specimen in a specially calibrated furnace mounted on the testing machine. The furnace was calibrated so that the temperature variations between seven thermocouples were only ±5° F. Upon reaching the desired temperature, the load was applied at the rate of 0.01 inch per minute per inch of gage length until the 0.2-percent yield strength was reached. The rate was then increased to 0.03 inch per minute per inch of gage length until rupture occurred. Stress-strain curves were obtained for each specimen.

Except for the difference in dimensions of the test pieces, the testing of the sheet material was somewhat similar to the procedures employed for the extruded stock. It was, however, extremely difficult to obtain accurate stress-strain curves because of the type of extensometer equipment. For this reason, only the ultimate strengths were obtained on the sheet specimens.

Creep Tests

The equipment used for creep testing is illustrated in figure 1 which shows a group of four creep or stress-rupture units. Each testing unit is equipped with a chromium-plated copper- or steel-shell furnace 6 inches in diameter and 18 inches long, wound with 14-gage Chromel A wire and insulated with silica gel. These furnaces may be used for creep or stress-rupture tests up to 1800° F, but 600° F was the maximum temperature employed in this investigation. A small window is provided at both the front and back of the furnace for measuring the deformation of the test specimen by optical means.

A standard 0.505-inch creep test specimen and calibration specimen are shown in figure 2. The temperature gradient in the furnace can be controlled and changed by means of external shunts along the tapped furnace winding. For this purpose, the calibration specimen, shown in figure 2, is used and the furnace is shunted so that the maximum temperature variations measured by thermocouples at positions T_i, C_i, B_i, T_o, C_o, and B_o do not exceed ±3° F at the test temperature. In some cases, even smaller variations are obtained. All temperature variations are kept below the maximum allowed by reference 6. During the actual creep tests, thermocouples are located at positions T_o and B_o and are used for adjusting the test temperature. Thermocouples are also placed at positions T and B, the control thermocouple at B and the recorder thermocouple at T. These thermocouples can be replaced while the test is in progress.

The load is applied to the test specimens by means of a lever arm with a 9:1 ratio. For the purpose of the present investigation, a stress

of 2000 psi was employed. Stresses of 1300 and 2500 psi were included for the evaluation of the experimental alloy of optimum composition.

The test temperature of each furnace is maintained by Tag Celectray indicating controllers equipped with a throttling mechanism for closer control. Foxboro controllers with a heater loop anticipating device are also used for control on some test units. For measurement of deformation, platinum strips are used which are attached to the shoulders of the specimen, one at each end of the gage length. Figure 2 shows the strips in position upon the test specimen. A series of very fine cross marks is ruled on each strip. Changes in length of the test specimen are measured by determining the change in distance between two chosen cross marks, one on each strip.

The microscope, with which deformation readings are made, has an eyepiece fitted with a filar micrometer and is mounted on a graduated screw. Calibration shows the smallest division of the filar eyepiece to read 0.00005 inch, which, on a gage length of about 2.3 inches, provides readings slightly over 0.00002 inch per inch, or about 0.002 percent.

Deformation readings are usually made daily by two observers, and the time-deformation data illustrated in this report are the averages of the readings obtained by two observers.

ALLOY DEVELOPMENT

Several experimental compositions had been prepared for the work on the development of forged alloys for elevated-temperature service reported in reference 5, but there was not sufficient time to complete the creep tests on all of the heats. All of these alloys contained an EM62 base, a designation which indicates that the magnesium-base alloys contained approximately 6 percent cerium and 2 percent manganese. The A.S.T.M. designation is EM61 because of the low minimum manganese content which is permissible. However, if the base alloys referred to in this report contained near 2 percent manganese, they will be referred to as EM62, EM42, or EM22, depending upon their cerium content. Actually, misch metal was used in all of the experimental work. Consequently, percent cerium actually means percent rare earths in the form of misch metal.

To complete the appraisal of the effects of various additions to the EM62 base, specimens of the material previously prepared were subjected to creep tests at 600° F and at a 2000-psi stress. The tensile properties of these alloys at room temperature and 600° F are presented in reference 5.

To recheck the effects of aluminum on the creep properties of the EM62 base, a new heat, A4850, was prepared and tested. The effect of the various additions on the minimum creep rate and total deformation in 120 hours is shown by the bar graph in figure 3. Included in this figure are several heats of EM62 prepared for the present investigation.

Reference to figure 3 shows, first of all, a considerable variation in the total deformation and minimum creep rate of the EM62 base. As will be pointed out later, this variation in creep properties of the EM62 base, as well as of the EM42 and EM22 bases, appears to be characteristic of these alloys in the extruded form.[1] Because of this variation in the creep properties of the base material, the conclusions which may be drawn from figure 3 can only be tentative, as follows:

(1) The addition of 0.5 percent aluminum appears to be somewhat beneficial and the results obtained on the new heat, A4850, check the previous results obtained on heat A3213 referred to in reference 5.

(2) In addition to 0.5 percent aluminum, it is probable that 0.01 percent titanium or 6 percent cadmium has some beneficial effect on the creep rates of the EM62 base material.

It should be noted that, while the creep properties of the alloys containing cadmium, titanium, or aluminum are considerably better than the average results obtained on the EM62 base, they are only slightly better than the best creep resistance obtained with the EM62 base.

The alloy-development phase of the present investigation was guided to some degree by the experiences and data obtained in the previous projects dealing with magnesium-cerium casting-alloy development. Seventy-five melts were prepared in the present investigation. A portion of these heats was prepared as part of the alloy-development program. The others were prepared as part of the fundamental investigation dealing with the relationship of composition and structure to the creep properties.

Effects of Manganese and Cerium Contents

A considerable study was made of the effects of manganese and cerium contents as part of the work required to obtain additional data to permit the establishment of the proper cerium and manganese contents of the base material. This study was also necessary in the phase of the project dealing with the relationship of composition and structure to the creep properties.

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[1]The creep resistance of these alloys in the standard creep test is remarkably consistent when the material is in the form of cast test bars.

The creep data showing the effects of manganese content are graphically represented in figures 4 and 5. The creep data showing the effects of cerium are graphically represented in figures 6 to 9.

The tensile data showing the effects of manganese and cerium contents are in tables 1 and 2.

Figure 4 consists of time-deformation curves showing the effect of manganese in an extruded magnesium-base 2-percent-cerium alloy in the heat-treated, aged, and stabilized condition. The tests were conducted at 600° F and a 2000-psi stress. It may be concluded from this figure that, in a 2-percent-cerium alloy, the creep properties at 0.81, 1.24, 1.55, and 1.90 percent manganese all produce about the same creep rates, at least up to 150 hours. Only the 1.90-percent-manganese alloy was tested to 621 hours. However, when the manganese content is reduced to 0 percent, the creep resistance is exceedingly inferior, since 20 times more deformation occurred in 50 hours than was obtained in the manganese-containing alloys in 150 hours.

Figure 5 contains time-deformation curves showing the effects of manganese in an extruded magnesium-base alloy containing 4 to 4.5 percent cerium. Again, the tests were carried out at 600° F and at a 2000-psi stress and the material was in the heat-treated, aged, and stabilized condition. There is some scatter in the results, but it may be concluded from this figure that 0 percent manganese again results in an alloy having exceedingly poor resistance to creep. There is some indication that the manganese content should be greater than 1 percent in this base material. However, this conclusion is tentative, since some scatter in the results occurred.

Figures 6 and 7 are time-deformation curves showing the effects of cerium content in 1.8-percent-manganese alloys in the heat-treated, aged, and stabilized and heat-treated, quenched, aged, and stabilized conditions, respectively. Figure 8 shows the effect of cerium on the time required to produce 0.1-, 0.2-, 0.5-, 1-, 2-, and 5-percent deformation in a 1.6- to 1.9-percent-manganese, magnesium-base, extruded alloy. As might be expected, the cerium content had relatively little effect on the time required to produce 0.1-percent deformation. However, at 0.5- and 1-percent total deformation, the optimum cerium content in the 1.6- to 1.9-percent-manganese alloys in the heat-treated, aged, and stabilized condition appears definitely to be near 2 percent cerium.

Figure 9 shows the effect of cerium on the minimum creep rate and total deformation at 120 hours. Again, the base material is a 1.6- to 1.9-percent-manganese, magnesium-base, extruded alloy. The testing temperature was 600° F and the stress was 2000 psi. This graph merely is another method of presentation of the data shown in figure 8. It is again concluded that the cerium content for maximum resistance to creep

is near 2 percent in the 1.6- to 1.9-percent-manganese alloy. This conclusion is further substantiated by the bar graph in figure 10.

The effect of manganese on the tensile properties at room temperature and 600° F is shown by the data in table 1. These data indicate the following:

(1) The yield strength at room temperature increases with manganese content up to about 1 percent in the 2-percent-cerium base, but the manganese is without effect on the yield strength of the 4-percent-cerium base.

(2) An addition to the 2-percent-cerium base of about 0.8 percent manganese, or more, produces some increase in ultimate strength at room temperature.

(3) The yield strength at 600° F increases with the manganese content in both the 2- and 4-percent-cerium alloys. No further increase in yield strength, however, is obtained at manganese contents higher than about 1.5 percent.

(4) In the 2-percent-cerium base, the ultimate strength at 600° F increases substantially with the manganese content up to about 1.25 percent. In the 4-percent-cerium base, the ultimate strength at 600° F increases only from about 10,125 to 11,000 psi as the manganese content is increased from 0 to 1.66 percent.

(5) The elongation at room temperature and at 600° F appears to be substantially independent of the manganese content in either the 2- or 4-percent-cerium base.

Thus, the best tensile properties, as well as maximum resistance to creep, are obtained by a manganese content of about 1.5 percent. Such manganese contents can be readily obtained in the magnesium-cerium melts, whereas manganese contents near 2 percent are relatively difficult to attain.

The effect of cerium content on the tensile properties is shown in table 2, which indicates the following:

(1) The yield strength at room temperature is somewhat variable though not appreciably affected by the cerium content

(2) The ultimate strength at room temperature is variable up to about 1 percent, above which it remains about 35,000 psi

(3) The elongation at room temperature does not appear to be materially affected by the cerium content, although there is a tendency for some reduction in elongation when the cerium content is in excess of 2.5 percent

(4) The greatest effect of cerium content is apparent in the results of the tests at 600° F

(5) The yield strength at 600° F more than doubles when the cerium content is increased from 0 to about 2 percent, above which content only a slight improvement is obtained

(6) The ultimate strength at 600° F increases from about 4000 psi at 0 percent cerium to about 10,200 psi at 2 percent cerium, and with only a slight further increase in ultimate strength when the cerium content is increased to approximately 4 or 6 percent

(7) The elongation at 600° F appears to increase slightly with increasing cerium content

Certainly, it may be concluded from the above data that about 2 percent cerium and about 1.5 percent manganese are the optimum amounts needed to produce good tensile properties at 600° F, as well as to attain maximum resistance to creep.

Effects of Additions of Other Elements to Nominal 2-Percent-Cerium, 1.7-Percent-Manganese, Magnesium-Base Alloys

In previous work (references 4 and 5) on the development of magnesium-cerium casting and forging alloys, it was found that small additions of nickel produce beneficial effects on the tensile and creep properties at 600° F. The 0.2-percent-nickel addition increased the tensile strengths of the 2-percent-cerium, 1.7-percent-manganese alloy at 600° F by approximately 2000 psi, and improved the resistance to creep at 600° F and a 2000-psi stress. Therefore, this element was employed either singly or in combination with other elements in 28 of the 75 melts prepared in the present investigation.

A summary of the data obtained on the heats prepared previously in the alloy-development phase of the project is contained in table 3. This table shows the actual analysis, methods of fabrication, heat treatments, testing temperatures, tensile properties at room temperature and at 600° F, and a summary of the creep data.

Figure 10 is a bar graph showing the total deformation at 120 hours and the minimum creep rate of several heats of the following:

(1) EM62

(2) EM42

(3) EM22

(4) Alloys containing 1.8 percent manganese and 0 to 1.35 percent cerium

(5) The alloy of optimum composition, namely, one containing 2 percent cerium, about 1.7 percent manganese, and about 0.2 percent nickel

(6) Several alloys of the optimum composition plus single additions of several other elements

Review of figure 10 and table 3 shows the following:

(1) The total deformation and minimum creep rates of the alloys in the heat-treated, aged, and stabilized condition are the highest for the EM62, lower for the EM42, still lower for the EM22 composition, and then increase again markedly at 0 percent cerium

(2) There is a very large amount of scatter in the data for the EM62, EM42, and EM22 alloys, and for the alloy containing 0.75 percent cerium and 1.8 percent manganese

(3) About 0.2 percent nickel in the nominal 2-percent-cerium, 1.7-percent-manganese, magnesium-base alloy with or without smaller additions of other elements produces consistently low creep values and thoroughly demonstrates the superiority of this alloy over EM22, EM42, or EM62 compositions in extruded form

(4) Small additions of aluminum, silver, cadmium, cobalt, molybdenum, strontium, tellurium, or tungsten made to the alloy of optimum composition did not produce an appreciable improvement in creep properties, at least in the standard creep test at 600° F and a 2000-psi stress

The titanium and nickel additions to the 1.7-percent-manganese, 2-percent-cerium alloy were ineffective probably because the 90-percent-nickel, 10-percent-titanium alloy added to the melt was relatively insoluble. Consequently, the data for heat A5456 in table 3 are actually representative of the values obtained on the EM22 base.

Small additions of aluminum appeared to have a beneficial effect on the creep resistance of a 6-percent-cerium, 2-percent-manganese alloy, and this observation was confirmed by further tests in the present investigation. However, in the base of approximately 2 percent cerium and 1.7 percent manganese a small aluminum addition did not appear to be

beneficial, as shown by figure 11. This figure consists of time-deformation curves for alloys containing approximately 2 percent cerium, 1.8 percent manganese, and 0.25 percent nickel, with and without a small addition of aluminum.

Alloy of Optimum Composition

As a result of the alloy-development phase of the project, the following composition appeared to possess the best properties and merited further study:

Cerium	2 percent
Manganese	1.7 percent
Nickel	0.25 percent
Magnesium	Balance

The range in composition has not been established, but it is likely that the cerium content should be within the range of 1.8 to 2.5 percent, the manganese 1.4 to 1.8 percent, and the nickel 0.2 to 0.3 percent.

The alloy of optimum composition was subjected to detailed tests as follows:

(1) Tensile tests at room temperature to 600° F

(2) Creep tests at 600° F and at 1300-, 2000-, and 2500-psi stresses

(3) Fabrication tests, including both forging and rolling

The comparison of the tensile properties of EM22 and of the alloy of optimum composition is illustrated by figure 12. This figure shows the tensile and yield strengths of the alloy at room temperature, 300°, 400°, 500°, and 600° F. Although the EM22 composition is slightly superior at room temperature, the alloy of optimum composition has substantially better properties at temperatures of 300° F and above. In general, both the yield strength and ultimate strength of the alloy of optimum composition are about 2000 psi higher than the values for the EM22 composition. At 600° F, this constitutes about a 20 percent increase in strength.

The comparison of the creep properties of EM22 with the similar creep properties of the alloy of optimum composition is shown in figures 13 to 16. Figure 13 shows a comparison of the two alloys at 600° F and a 1300-psi stress. Under these conditions, the two alloys appear quite similar and the minimum creep rate is very low for both materials.

Figure 14 shows the time-deformation curves for the two alloys at 600° F and under a 2000-psi stress. In this chart, three different heats of EM22 and three different heats of the experimental alloy of optimum composition are shown. The superiority of the alloy of optimum composition is quite evident. The total deformation of the experimental alloys at the end of 500 hours is one-half that of the best heat of EM22 and one-fifth that of the poorest heat of EM22. Figure 15 shows additional data obtained under the same conditions as those illustrated by figure 14. Four additional heats of EM22 are shown along with one heat of the experimental alloy of optimum composition. The creep rates of the four heats of EM22 vary widely and all are inferior to that of the experimental alloy of optimum composition.

Figure 16 shows the time-deformation curves for one heat of EM22 and two heats of the experimental alloy of optimum composition at 600° F and a 2500-psi stress. Again, the data for the experimental alloy are consistent. The total deformation for the experimental alloy at the end of 300 hours is approximately one-thirteenth that obtained on the EM22 composition.

Figure 17 shows a summary of the creep data obtained on the EM22 alloy and the experimental alloy of optimum composition. This figure shows design curves and consists of a plot of the stress against the logarithm of the time in hours required to produce 0.1-, 0.2-, 0.5-, 1-, and 5-percent total deformation. The superiority of the experimental alloy of optimum composition is quite evident. Thus, under a stress of 2500 psi, 0.5-percent deformation will be reached in the EM22 composition in 60 hours, whereas the experimental alloy of optimum composition will support the same stress for 500 hours before the same total deformation is produced.

Figures 18 and 19 show photomicrographs of the experimental alloy of optimum composition at a magnification of 250X. Figure 18 shows the alloy in the heat-treated, aged, and stabilized condition, the heat-treating temperature being 1040° F. Figure 19 shows the same alloy in the same condition after employing a heat-treating temperature of 1000° F. The tensile properties of the alloy at room temperature and 600° F are the same for both heat-treating temperatures. However, as shown by the data given with the photomicrographs, the creep resistance of the alloy heat-treated at 1040° F is markedly superior to the creep resistance of the same material heat-treated at 1000° F. It is quite possible that the greater creep resistance of the alloy heat-treated at 1040° F is a result of the coarser grain produced. Several of the experimental alloys of optimum composition heat-treated at 1040° F have been examined metallographically and none show any voids produced by burning at this temperature.

The metallographic examination of the surface corrosion produced by exposure to 600° F for 600 hours showed that the attack was superficial and even less in 2-percent-cerium alloys than in alloys of higher cerium content. The specimens listed in the table below were examined microscopically to determine the degree of surface oxidation. The exposed creep test bars were measured by means of a micrometer in the condition as removed from the furnace. After measuring, the loose scale was removed by means of a wire brush and the bars again measured. The difference between the two readings indicates the thickness of the adhering scale. The difference between the final diameter and the original indicates the over-all loss resulting from the exposure at 600° F.

The depth of penetration of the oxidized layer was measured. This was done by use of the filar micrometer at 100X, and the depths of oxidation are reported in microns as follows:

Specimen	Alloy	Time (hr at 600° F)	Diameter (in.)			Net decrease in diameter (in.)	Depth of surface oxidation (μ)
			Original	After exposure (a)	After cleaning		
A5277-X7	EM62	533	0.5046	0.501	0.498	0.0066	36-53
A5277-X5	EM62	458	.5050	.493	.489	.016	44-80
		[b]495					[b]54
A5462-X5	EM22	434	.505	.510	.503	.002	16-34
A5262-X5	EM22	500	.505	.509	.502	.003	12-16
		[b]467					[b]20
A5600-X5	Exp.	509	.5045	.507	.503	.0015	37-45
A5465-X5	Exp.	600	.5045	.507	.503	.0015	24-34
		[b]555					[b]35

[a]Diameter with the scale intact.
[b]Average.

It is concluded that the EM22 and experimental alloys oxidize at about the same rate and both are more resistant than the EM62 alloy. While the degree of oxidation in 500 hours at 600° F is minor, the alloys should be protected if they are to be exposed for longer times. Previous work (reference 5) has shown that cast bars of EM62 treated by the following method were more resistant to oxidation at 600° F than untreated specimens. The specimens were first degreased for 5 to 15 minutes in the following bath at 180° to 240° F, using a current density of 15 amperes per square foot:

Trisodium phosphate	240 grams
Sodium carbonate	240 grams
Distilled water	8.0 liters
Cold-water rinse	

After degreasing, the specimens were treated for 10 minutes in the following bath at room temperature:

Hydrofluosilicic acid	250 ml
Distilled water	750 ml
Titanium potassium oxalate added to saturation point	

After the specimens were removed from the fluosilicic-acid bath, they were rinsed in cold water, dipped in hot water, and dried in an air blast.

Fabrication Tests

Fabrication tests were made on ingots of EM22, EM42, and EM62, on ingots of the experimental alloy of optimum composition, and on ingots containing small additions to this optimum composition. The objective was to evaluate the relative hot-working characteristics of the alloys and to find small additions which would impart improvement in fabricating characteristics without a sacrifice in high-temperature properties. A slab 1 inch or $1\frac{1}{4}$ inches thick, chill-cast in an iron mold, was used for the tests. The slabs were usually scalped prior to rolling or after they had been hot-rolled to 3/4-inch thickness. Rolling tests were carried out on several ingots, with the results listed in table 4. In general, the 6-percent-cerium alloys hot-rolled with greater difficulty at 1000° F than did the lower-cerium alloys. Some additions, notably 0.5 percent aluminum, improved the hot-rolling characteristics. It is quite evident, also, that the optimum hot-rolling temperature is 925° to 1000° F. The hot-rolling characteristics of the alloy of optimum composition appeared to be satisfactory, though slightly inferior to those of EM22.

A few forging tests were also conducted on EM42 and on the experimental alloy of optimum composition. These tests were carried out with the use of an air-driven drop hammer. The dies were not preheated prior to the tests. It was found that the round extrusion ingots prepared by the water-cooled process, as described previously in this report, were not suitable for forging tests. Consequently, the alloys were chill-cast into ingots 5 by 5 by 8 inches high. The ingot mold employed was gray iron fitted with a copper bottom. The top of the mold was also equipped with a refractory hot top to promote adequate feeding of the ingot during solidification. Experimental forging tests were performed on five heats, with the results listed in table 5. Although the tests

were too limited to permit definite conclusions, the alloy of optimum composition appears to forge about as well as EM42 alloy. The optimum forging temperature appears to be about 950° F, as shown by preliminary tests not recorded in table 5.

Effect of Fabricating Procedure on Properties of the Alloys

Several of the compositions were tested in the cast, extruded, and rolled conditions. It was found that the method of fabrication had a considerable effect upon the properties at room temperature and at 600° F. Table 6 shows the tensile and creep properties of several alloys fabricated by different methods. The materials tested at room temperature are in the heat-treated and aged condition, whereas those tested at 600° F are in the heat-treated, aged, and stabilized condition.

As would be expected, the castings have the lowest tensile properties at room temperature. The 0.060-inch rolled sheet has tensile properties, particularly yield strength at room temperature, somewhat inferior to the properties of the extrusions. At 600° F, the tensile properties of the extrusions are equivalent to or slightly better than those of the castings, whereas the tensile properties of the sheet are again somewhat inferior to those of the extrusions. The average creep values obtained on 13 extruded specimens, 8 cast specimens, and 4 sheet specimens of about 2 percent cerium and 1.7 percent manganese, with or without nickel, were as follows:

	Castings	Extrusions	Sheet
Minimum creep rate, percent/hr	0.0002	0.0012	0.010
Total deformation, percent in 120 hr	0.096	0.244	1.844

The average minimum creep rate of the castings in the standard test is the lowest of the three types of specimens, that of the extrusions 6 times higher than that of the castings, and that of the 0.060-inch sheet about 12 times higher than that of the extrusions. When comparing the total deformation at 120 hours, the value for the sand-cast material is again the best, and that for the extruded material is about $2\frac{1}{2}$ times greater than that of the castings, whereas the total deformation of the 0.060-inch rolled sheet is about 7 times that of the extruded material. The differences in the creep and tensile properties obtained on extruded and sheet materials can, in part, be attributed to the differences in physical shape of the specimens.

RELATIONSHIP OF COMPOSITION AND STRUCTURE TO CREEP PROPERTIES

Effect of Heat Treatment

The relationship of creep properties to the structure of the alloy was first approached by investigating the effects of heat treatment on cast and forged materials. Obviously, the amount of soluble alloy-rich compound in solution at the heat-treating temperature and the degree of precipitation of the material in solution can be controlled by the solution treatment, the quenching rate, and the aging temperature employed. Five heats, A4928, A4929, A4930, A4931, and A4932, of EM42 composition were prepared. These were cast in the form of test bars in green-sand molds and in the form of extrusion billets, using the water-quenching technique described earlier in the report. Specimens from each of these heats, both cast and extruded form, were heat-treated as follows:

(1) Heated for 16 hours at 400° F and air-cooled

(2) Aged 16 hours at 400° F and stabilized 24 hours at 650° F

(3) Solution-heat-treated 24 hours at 1040° F, air-cooled, and aged 16 hours at 400° F

(4) Solution-heat-treated 24 hours at 1040° F, air-cooled, aged 16 hours at 400° F, and stabilized 24 hours at 650° F

(5) Solution-heat-treated 24 hours at 1040° F, quenched in cold water, and aged 16 hours at 400° F

(6) Solution-heat-treated 24 hours at 1040° F, quenched in cold water, aged 16 hours at 400° F, and stabilized 24 hours at 650° F

(7) Solution-heat-treated 24 hours at 1040° F, oil-quenched, and aged 16 hours at 400° F

(8) Solution-heat-treated 24 hours at 1040° F, oil-quenched, aged 16 hours at 400° F, and stabilized 24 hours at 650° F

The effects of these treatments on the tensile and creep properties are shown by the data in table 7. The following conclusions may be drawn from this table:

(1) In the sand-cast condition, the highest tensile strength at room temperature is obtained by solution-heat-treating, but it does not make much difference whether the casting is air-cooled or quenched from the solution temperature.

(2) Because of the lack of stabilization of the sand castings, aging alone produces the highest yield and highest ultimate strengths at 600° F. Aging and stabilizing is second best, while specimens given a solution heat treatment have slightly lower ultimate and yield strengths at 600° F. The rate of quench from the solution temperature has relatively little effect. It may be concluded, therefore, that solution-treating followed by aging and stabilizing produces slightly lower yield and ultimate strengths than aging and stabilizing prior to testing at 600° F.

(3) The various heat treatments have relatively little effect upon the creep rate of castings of EM42 at 600° F under a 2000-psi stress.

(4) The aged and stabilized extruded material has the lowest yield and ultimate strengths at room temperature. The highest room-temperature tensile properties were obtained by quenching from the heat-treating temperature.

(5) The yield strength and ultimate strength of the extruded material at 600° F are improved slightly by solution-heat-treating and, again, quenching from the solution temperature produces slightly higher properties.

(6) Although the data are somewhat limited, the creep resistance of the extrusions appears to be poorest in the aged and stabilized conditions, intermediate in the aged condition, and best in the heat-treated, aged, and stabilized condition. The effect of quenching from the solution-treating temperature appears to be quite variable. When data on specimens from the same heat are compared, quenching appears to be fairly beneficial on this alloy.

(7) Relatively few data are available on the rolled sheet, but obviously the creep resistance of the sheet is substantially inferior to that of the extruded material. The sheet in the aged condition is markedly inferior to that in the heat-treated, aged, and stabilized condition.

In addition to the above studies on the effects of heat treatment, a series of alloys containing approximately 1.7 percent manganese and 0 to 6 percent cerium was tested in the annealed, the heat-treated, aged, and stabilized, and the heat-treated, quenched, aged, and stabilized conditions.

The effect of annealing on the creep resistance of a series of alloys containing various amounts of cerium is shown in table 2. It seems evident from these data that any treatment which tends to precipitate and coagulate the phase which was once in solution has a very adverse effect upon the creep rate. On the other hand, solution-treating, aging, and stabilizing the extruded material produce substantially better

creep resistance than aging and stabilizing alone (table 7). Thus, the solution of the soluble phase appears to be beneficial, even though it must be precipitated in a fairly fine state of division during the aging and stabilizing treatments.

Figure 6 shows the time-deformation curves for the 0- to 6-percent-cerium series in the heat-treated, aged, and stabilized condition, while figure 7 shows a similar set of curves for the same series in the heat-treated, quenched, aged, and stabilized condition. A comparison of figures 6 and 7 and the data graphically represented by figures 20 to 22 shows some remarkable effects as follows:

(1) In the heat-treated, aged, and stabilized condition, the 0-percent-cerium alloy, namely, M1 alloy, has the poorest resistance to creep, but in the heat-treated, quenched, aged, and stabilized condition, the M1 alloy has the best resistance to creep although there is a tendency to enter third-stage creep at a fairly early period. Since this result was obtained on duplicate heats, the remarkable effect of quenching M1 alloy appears to be real. The effect of heat-treating M1 alloy is shown in detail in figure 20. Obviously, a rapid quench has a markedly beneficial effect, and annealing from the solution-heat-treating temperature has an exceedingly harmful effect.

(2) The EM22 alloy appears to be damaged by quenching from the solution temperature. However, this effect, shown in detail by figure 21, may not be real since a considerable variation in creep sometimes occurs in material from the same heat. It should be noted, however, that annealing EM22 alloy has a very adverse effect on the creep rate, as shown by figure 21.

(3) A 0-percent-manganese, 2.33-percent-cerium alloy has the best resistance to creep in the heat-treated, quenched, aged, and stabilized condition, the second best in the heat-treated, aged, and stabilized condition, and the poorest in the annealed condition, as shown by figure 22. However, it will be observed that all of these specimens, regardless of heat treatment, have very poor resistance to creep. It may be concluded, therefore, that cerium alloys in the absence of manganese have very poor resistance to creep. However, as noted earlier, the cerium greatly improves the tensile properties at 600° F.

(4) The M1 alloy in the heat-treated, quenched, aged, and stabilized condition has good resistance to creep and very poor tensile properties (see table 2), whereas the 2-percent-cerium alloy has good tensile properties and very poor resistance to creep. This forms an outstanding example of the lack of correlation between tensile properties and creep properties.

The data presented so far definitely indicate that it is mainly the manganese, and perhaps the cerium in solution at the heat-treating temperature which has a beneficial effect on the creep properties. Cerium imparts good tensile properties at 600° F, but it is the manganese which imparts good creep resistance. It should be noted, however, that the employment of both cerium and manganese in an alloy makes it possible to obtain good creep resistance without rapid quenching from the solution temperature. While these factors certainly are the underlying ones determining the creep properties of the magnesium-cerium-manganese alloys, there are many variations from heat to heat and even from one test specimen to another from the same heat which are not easily understood. Accordingly, further studies were made by the use of metallography, X-ray diffraction, and the electron microscope. These studies are discussed in later sections of this report.

Effect of Orientation on Creep Properties of EM22 Sheet

It is quite probable that the crystallographic orientation may have some influence on creep rate. Thus, the differences in crystallographic fibering may be one cause of the differences in creep resistance noted for castings, extrusions, and sheet.

Duplicate specimens parallel to and transverse to the direction of rolling were tested in creep at 600° F and a 2000-psi stress with the following results:

Property	Parallel	Transverse
Tensile strength, room temperature, psi	26,550	26,700
Elongation, room temperature, percent	9.8	8
Tensile strength, 600° F, psi	8300	7100
Elongation, 600° F, percent	51	40
Minimum creep rate, percent/hr	0.0055	0.0065
(Duplicate specimens)	0.0165	0.012
Total deformation in 120 hr, percent	0.75	0.812

These results indicated relatively little difference in creep resistance of the parallel and transverse specimens, though some difference in preferred orientation probably occurred. No further tests were made; therefore the degree of preferred orientation in the specimens was not established.

The path of fracture of magnesium-cerium alloys was not investigated. However, this subject was investigated at the Wright-Patterson Air Force Base and has been described informally to the present authors as follows: "Briefly, fractures at room temperature and 400°F. were through the

Mg_9Ce compound. Flow adjacent to the fracture at 600°F. fragmented the Mg_9Ce network and fracture was transcrystalline without regard to the Mg_9Ce phase. No difference could be noted between tensile-test fractures and stress-rupture fractures." Apparently, this study was on castings since these magnesium-cerium networks do not occur in forged alloys.

Metallographic Examination

The study of the effects of heat treatment and cerium and manganese contents apparently developed the basic factors determining the creep properties of magnesium-cerium-manganese alloys. However, many variations in creep resistance occurred from heat to heat or from specimen to specimen from the same heat. These differences in creep resistance require clarification before all of the factors determining the creep resistance can be understood. In order that some information on this problem might be obtained, metallographic examination was made of a large number of specimens, some of which showed various degrees of resistance to creep as listed in table 8. Specimens were selected because the differences in creep resistance apparently were the result of a known difference in composition, heat treatment, or in fabrication. Other sets of specimens examined metallographically were of similar compositions but from different heats, and other pairs of specimens possessed differences in creep even though they were from the same heat of metal.

Figures 23 to 32 show photomicrographs of various representative specimens. From these metallographic studies of the specimens listed in table 8, the following conclusions were drawn:

(1) Cerium has a definite grain-refining action on the M1 alloy, but relatively little additional grain-refining action is produced by increasing the cerium content above 2 or 2.5 percent.

(2) At the heat-treating temperature of 1040° F, the solubility of cerium in the 1.7-percent-manganese, magnesium-base alloy appears to be near 1.3 percent. With greater amounts of cerium, the portion of the cerium-rich phase not in solution increases in amount.

(3) As shown by figures 23 and 24, the metallographic examination has not revealed the cause of the remarkable improvements in creep produced by quenching M1 alloy.

(4) The cause of the very poor creep resistance of the manganese-free alloys is not apparent in figures 25 and 26.

(5) Figures 27 to 29 show a 1.34-percent-cerium, 1.56-percent-manganese alloy in the heat-treated, aged, and stabilized, the heat-treated, quenched, aged, and stabilized, and the annealed conditions.

Quite obviously, the coagulation of the alloy-rich phase in the annealed specimen (fig. 29) accounts for its poor creep resistance.

(6) Figures 30 to 32 show EM62 alloy in the heat-treated, aged, and stabilized, the heat-treated, quenched, aged, and stabilized, and the annealed conditions. Again, the annealing treatment has coagulated the fine structure within the grains and produced low creep resistance. In this instance, the heat-treated, quenched, aged, and stabilized specimen (fig. 31) possesses the greatest amount of fine structure within the grains and has the highest resistance to creep. However, the examination of many specimens under the microscope did not show a definite correlation between the amount of this fine structure within the magnesium grain and the resistance of the specimen to creep.

Since the conventional metallographic examinations were not very revealing, they were supplemented with X-ray diffraction and electron-microscope studies.

X-Ray Diffraction Studies

Experimental procedure.- The samples examined by X-ray diffraction are listed in table 8. All of these samples are extrusions, except for the cast bar. Samples of the creep test bars for phase identification were obtained from the test section of the bars by filing a cross section. This procedure should obtain filings of a representative part of the cross section, including material from the center as well as from the periphery of the sample tested in creep. Samplings of the grip ends were not taken.

Diffraction photograms of the filings were found to show diffraction patterns of the extra phases as well as of the matrix magnesium terminal solid solution.

Attempts were made to dissolve the matrix metal phase and collect residues of the intermetallic compounds in the alloys. One test was made by using a Grignard reagent on the cast bar, A4975-A1. A few extractions were made using ammonium-chloride solutions of either two or four times normal strength, because it is known that magnesium dissolves in ammonium salts even though they are not highly acidic. Low acidity is desirable to reduce the possible rate of attack on metallic phases other than the matrix.

The diffraction photograms of the Grignard residue showed only reflections that were observed in the filings of some of the alloys, but the photograms were so weak that it was concluded that a large portion of the residue was amorphous. It is believed that the amorphous material may have been a product of a reaction between the residue and the ether

vehicle. The ether should have been replaced immediately after the Grignard treatment with a more inert organic solvent.

The first test of ammonium chloride as a means of producing an extraction residue was a rough one in which ammonium chloride of about twice normal strength was used and the dissolution of the sample was allowed to go on for only a short time. A small amount of black residue became separated from the sample in the solution. This residue was washed by decantation and dried with alcohol. The X-ray diffraction photogram was nearly similar to that from the Grignard extraction, but included a pattern which could be interpreted as a slightly expanded face-centered-cubic cerium dioxide. Hence, it was feared that some oxidation had occurred in the extraction procedure.

However, the use of the ammonium chloride of four times normal strength was tried again on the M1 alloy, specimen A5257-X5, for a short-time partial extraction; beta manganese was definitely detected in the diffraction photogram along with a moderate amount of some other material. The pattern was slightly spotty, indicating fairly coarse particles that could not have been formed by electrochemical deposition. Comparison of this photogram with those of the Grignard extraction and the concentrated ammonium-chloride extraction of the cast EM22 alloy then confirmed the presence of beta manganese in the ternaries. Examination of the various photograms of the filings indicated that beta manganese is present in at least some of the ternaries, but not all patterns were intense enough to show more than the strongest reflection of this phase. It was concluded that satisfactory extractions of metallic constituents in these alloys can be obtained, in some instances at least, by short-time dissolution in concentrated ammonium chloride, but not by long-time dissolution in dilute solutions. A continuation of the extractions on other samples and further improvement of the procedure would be very desirable.

Results of phase-identification work.- Satisfactory X-ray diffraction photograms showing extra reflections not belonging to the magnesium-rich terminal solid solution can be obtained from all the heat-treated alloys of the group studied. The reflections of the magnesium terminal solid solution are sharp, even in the back-reflection direction.

Compounds containing the alloy elements are susceptible to easy detection because both cerium and manganese are of considerably higher atomic number than magnesium and, therefore, tend to produce diffraction patterns which are relatively intense compared to the actual proportion of the compound phase present.

An attempt was made to identify each phase which appeared in the photograms of the filings. To facilitate this identification, the literature was searched for X-ray and constitution data on magnesium-manganese, magnesium-cerium, and manganese-cerium compounds. The

literature shows no evidence of magnesium-manganese compounds, but satisfactory X-ray data on the allotropic forms of manganese are available. Beta manganese was definitely detected in many of the alloys, while in others, the patterns were not intense enough to determine whether the phase was alpha or beta manganese. There is evidence that alpha manganese may be present in some specimens.

A standard pattern of the magnesium-cerium compound MgCe is available which shows the phase to be simple cubic with a lattice constant of 3.898 A. The compound Mg_3Ce is reported to be face-centered cubic with a lattice constant of 7.37 A. The magnesium-cerium alloy containing 35 percent cerium (actually, 35 percent misch metal) should be 8.6 atomic percent cerium, which composition lies close to Mg_9Ce in the Mg + Mg_9Ce field. In addition to a weak pattern of terminal magnesium phase, a strong diffraction pattern was obtained from this alloy, which was neither that of MgCe nor Mg_3Ce. This pattern is assumed to be that of Mg_9Ce. The Y-phase, observed in some of the ternary alloys, has been tentatively identified as Mg_9Ce.

No data on the manganese-cerium system were located.

It would be expected that the intermetallic compounds of the other rare-earth elements in the misch metal would be isomorphous with cerium compounds and form the same compounds as cerium. If not, the cerium compounds might take the other rare-earth elements in solid solution. The magnesium-cerium and magnesium-lanthanum constitution diagrams have the same compounds but lack the magnesium-praseodymium Mg_9Pr phase. The compounds Mg_3Ce, Mg_3La, and Mg_3Pr are isomorphous and have nearly the same cell size. The same relation exists between the compounds MgCe and MgPr.

In a few instances, ferritic iron and, in two instances, austenitic iron were detected in the filings. These phases were undoubtedly brought into the samples during filing, though this does not usually occur in filing magnesium.

The results of the phase-identification studies are listed in table 9.

Manganese is present in the form of the terminal solid solution of beta manganese in all the ternary alloys. Enough magnesium or cerium must be dissolved in this phase in some instances to make it stable at lower temperatures. In other alloys, alpha manganese may be present.

The X-phase, which appears to be face-centered cubic with a lattice constant of 5.50 to 5.60 A, is found in all the ternary alloys except specimen A4975-X8 (EM22), which is annealed. Its absence in this sample is associated with very poor creep properties. It was not detected in

the cast bar A4975-A1 (EM22 - HTAS[2]), except near the center. These two facts indicate that it is affected by heat treatment and cooling rate in the casting. However, if it is truly face-centered cubic with such a low lattice constant, it cannot be an intermetallic compound among magnesium, cerium, and manganese, but may be a chemical compound containing some small atoms such as oxygen, nitrogen, and carbon. The lattice constant of face-centered-cubic cerium oxide is 5.40 A. However, if X-phase is not cubic with the 5.50 to 5.60 A lattice constant, but merely appears to be, it could be a true intermetallic compound of the principal elements in the alloy - possibly a ternary compound.

It is practically certain that Y-phase is the compound known as Mg_9Ce, for the reflections which are used to detect Y-phase in the photogram of the ternary alloys are also present in the photogram of the alloy made up to have a composition of 8.6 atomic percent cerium. The strongest reflections of the Mg_9Ce phase are, unfortunately, masked in the ternary alloys by the rest of the photogram, making positive identification difficult.

It is possible that Mg_9Ce is simple cubic with a lattice constant of 7.30 A, for such reflections, together with a few others, appear in the photogram, but other reflections appear which indicate it is not cubic. This pseudolattice constant compares with a lattice constant of 7.37 A for Mg_9Ce, which is face-centered cubic. This relationship indicates some similarity between Mg_9Ce and Mg_3Ce.

Discussion of the X-ray data.- The slight diffusing of the beta-manganese pattern in the heat-treated, quenched, aged, and stabilized bar of the M1 binary indicates that the particle size of this phase in the heat-treated, quenched, aged, and stabilized treatment is smaller than in the unquenched sample. Small particle sizes of beta manganese also occurred in the magnesium-cerium-manganese ternaries, specimens A4975-X6 (EM22 - HTQAS[3]); A4931-X7 (EM42 - HTAS); and A4974-X5 (EM42 - HTAS). The minimum creep rates of the specimens were 0.0035, 0.0014, and 0.0034 percent per hour, respectively, and all represent fairly typical values for these alloys.

The absence of X-phase in the annealed EM22 bar, A4975-X8, is associated with the very high creep rate. The sharpness of the pattern of this phase does not appear to be directly related to creep rate.

In several instances, the presence of a substantial intensity in the pattern of Y-phase is associated with poor creep rates. A comparison of the two supposedly identical bars of A4931-X1 and -X7 (EM42 - HTAS) indicates that the bar having the poorer creep rate shows a Y-phase

[2]Heat-treated, aged, and stabilized.

[3]Heat-treated, quenched, aged, and stabilized.

pattern of considerably higher intensity. The bar of A4975-X5 (EM22 - HTAS), which had a low creep rate, showed only a trace of Y-phase, whereas the bars of the same heat in the heat-treated, quenched, aged, and stabilized and the annealed conditions showed substantial amounts of Y-phase. Bar A4849-X5 (EM22 - HTAS), which exhibited a high creep rate, also shows Y-phase in substantial amounts.

The correlation of poor creep rate with Y-phase fails, however, in bar A4974-X6 (EM42 - HTQAS), which has good creep rate despite a substantial amount of Y-phase. Here a diffuse pattern of X-phase occurs, whereas a sharp pattern is found in the air-cooled bar, A4974-X5 (EM42 - HTAS), which exhibited a higher creep rate.

The nickel-bearing bar, A4976-X5, of low creep rate (0.00025 percent/hr) also showed a very weak X-ray pattern of Y-phase. The apparent tendency of Y-phase to be associated with high creep rates, however, may indicate that this phase is important in some as yet unknown manner. One should expect the distribution and mode of occurrence of a phase to be more important than the quantity present. In fact, the large Y-phase particles, as shown by the photomicrographs (figs. 25 to 32) have little effect on the creep resistance, and may even be harmful. However, the above clues may serve as a basis for profitable optical- and electron-microscope study of these alloys in the future.

The cast bar, A4975-A1 (EM22 - HTAS), is quite different from the extruded specimens. The diffraction pattern of the matrix phase from the bulk of this bar is difficult to interpret. It appears to indicate both shrinkage and expansion of the magnesium lattice due to coring by the manganese and cerium additions, respectively. The center of the bar does not show this effect and exhibits an intense X-phase pattern in addition to the matrix.

The material in relief next to the grain boundaries in the electron micrographs of A4849-X5 (EM22 - HTAS), A4975-X6 (EM22 - HTQAS), and A4975-X8 (EM22 - annealed) may be Y-phase. This grain-boundary phase was not observed in electron micrographs of A4975-X5 (EM22 - HTAS) which had the lowest minimum creep rate of these four specimens. Little, if any, Y-phase was observed in this specimen by X-rays. Grain-boundary precipitation has been found in at least one other alloy system (reference 7) to be apparently associated with increased creep rate.

Electron Microstructure of Magnesium Alloys Containing Cerium and Manganese

The study of the microstructure of magnesium alloys using the electron microscope is quite difficult. Magnesium is very difficult to

polish for ordinary metallographic examination, and this difficulty is magnified when the specimen is to be studied in the electron microscope. Rough polishing followed by deep etching is a possible technique, but it is apt to obscure fine detail, especially that of fine particles of a second phase such as are present in age-hardened material. Therefore, the etching and replica technique recommended by Heidenreich (reference 8) for magnesium alloys was not used.

When replicas of lightly etched surfaces are to be made, two major problems arise. The disturbed metal resulting from polishing must be removed, and the formation of surface films which are not uniform and closely adherent must be prevented.

Repeated polishing and etching is the best way to eliminate the effects of disturbed metal. This process must be continued until replicas taken from the etched surface show a constant structure. Since the preparation of a single sample for electron microscopy requires considerable time, polishing and etching to obtain a constant structure is a long process. In this work, all samples were polished and etched at least six times, and the structures appearing in the resulting micrographs appear constant and reproducible.

Because magnesium is so susceptible to attack by the etchant, it is very difficult to devise an etching technique which will reveal the structure within a grain of the alloy without leaving a corrosion film. Various techniques have been tried and the one which was finally used was not entirely satisfactory. The etching bath consisted of 60 parts of ethylene glycol and 20 parts of acetic acid. The sample was etched for 30 seconds, then rinsed in absolute alcohol, then in ethylene dichloride, and finally in a solution of 2 percent Formvar in ethylene dichloride. During this process, the sample was never exposed to air or allowed to become dry. The Formvar solution was then allowed to dry so that the sample was protected by a thin film of plastic. This thin film was stripped from the sample, using Scotch tape. The sample was then quickly covered with a 0.4-percent solution of Formvar in ethylene dichloride and dried under a heat lamp with the polished face held vertical. This replica was backed with Zapon and stripped from the sample. The Zapon was removed from the replica by dissolving it in amyl acetate, a solvent which does not attack Formvar.

Because there was not time to examine all of the specimens, five were chosen for study. Four of these samples, A4975-A1, -X5, -X6, and -X8 (cast EM22 - HTAS and extruded EM22 - HTAS, HTQAS, and annealed, respectively), were from the same heat. Because of the methods of fabrication and heat treatments used, this set of specimens exhibited widely varying creep properties ranging from the best to the poorest. The other specimen, A4849-X5 (EM22 - HTAS), had a slightly different composition and had intermediate creep properties.

Some results from this study are shown in figures 33 to 38, which show samples having identical composition, with the exception of specimen A5107 in figure 35 which was used to establish a base line for comparison with the magnesium-cerium alloys.

All of the samples shown in these figures have at least two easily distinguishable phases. The matrix is apparently the terminal magnesium-rich solid solution. The phase which is found along the grain boundaries and sometimes within the grain is not yet identified, although, as indicated below, it may be the Y-phase or Mg_9Ce. It has a characteristic nodular appearance. Other phases which are shown to be present by X-ray diffraction data cannot be positively identified in the electron micrographs. The appearance of the grain boundaries does change slightly when one compares the alloy with the best creep properties with the alloy having poor creep properties. In the samples shown in figures 36 and 37, there is a constituent parallel to the grain boundary which does not etch so fast as the rest of the grain. The presence of this constituent seems to correlate with the presence of Y-phase as shown by X-ray diffraction. This slow-etching phase does not appear at the grain boundaries in figures 33 and 34, specimen A4975-A1 (cast EM22 - HTAS), in which little or no Y-phase was detected, nor was it found in electron micrographs of specimen A4975-X5 (extruded EM22 - HTAS), but was seen in specimen A4975-X6 (extruded EM22 - HTQAS).

Slip lines can be seen in some of the stressed specimens; they are especially prominent in figure 34. One micrograph in figure 38 shows numerous shallow pits where platelike particles may have been etched out.

Comparison of Results of X-Ray Diffraction and Electron-Microscope Examination

According to the X-ray results from the study of magnesium-base alloys, definite changes in constitution of the alloys occur with variation in heat treatment. Beta manganese (and, possibly, also alpha manganese) is present in these alloys, but its existence does not correlate with the creep properties. Unfortunately, attempts to detect it in the manganese binary alloys by the use of the electron microscope were unsuccessful. This is, however, believed to be only a question of techniques, since it has been shown by previous workers to exist as platelets in the matrix grains. It is possible that the platelike particles in figure 38 may be the manganese phase.

The Y-phase, tentatively identified as Mg_9Ce, appears in a cerium-binary alloy and in several of the ternaries. There is conflicting evidence as to correlation of the presence of Y-phase with creep properties, but the trend is that Y-phase is detrimental. The grain-boundary

phase appearing as small slow-etching particles in the electron micrographs of the magnesium, 2.3-percent-cerium binary (fig. 35) may be Y-phase. The large particles of Y-phase, found in the light micrographs of this sample, were not recorded in the electron micrographs. The large mottled nodules appearing in the grain boundaries in figures 33, 34, 36, and 38 are probably not Y-phase.

The X-phase is not identified, but it is associated with the presence of cerium. This is probably not MgCe or Mg_3Ce, and may be an unknown ternary compound. There is evidence that X-phase disappears as Y-phase increases. The X-phase has not been positively identified in the electron micrographs, but may be the mottled nodular material.

There is some evidence that the precipitation of Y-phase is detected in the electron micrographs in the regions along the edges of the grain boundaries where etch attack is less rapid. This effect is seen in figures 36 and 37 as a bright outline around the grain boundaries; Y-phase was present in this sample. The Y-phase in the cerium-binary alloy, seen in relief in figure 35, is also characterized by slow etching.

The scope of these fundamental studies is of a preliminary nature only. It is obviously necessary to identify X-phase and to determine its significance as a factor affecting the creep rate. The potential value of the electron microscope is demonstrated in the accompanying micrographs, even though they represent a rather undeveloped technique employed only to survey the field. The etching technique requires careful attention to bring out more detail. In most cases, for example, little detail in the structure of the matrix grains was developed by the etchant used. It is possible that precipitation from the matrix is an important factor with respect to creep, and it should certainly be possible to show this with other etchants. The replica technique used was chosen primarily for speed and simplicity. Other methods are commonly used which have been shown to reveal considerably more detail with higher resolution.

SUMMARY OF RESULTS

An investigation of magnesium-cerium alloys was made to develop improved alloys and to study the correlation of alloy composition and structure with the resistance to creep. The results of this investigation may be summarized as follows:

1. The alloy-development phase of the project was brought to a logical conclusion and no further alloy development appears to be necessary. The nominal composition of the recommended alloy is

Manganese	1.7 percent
Cerium	2 percent
Nickel	0.25 percent
Magnesium	Balance

This alloy should be solution-heat-treated at 1040° F. In the experimental work, the alloys were heat-treated 24 hours at 1040° F, air-cooled, and then aged 16 hours at 400° F.

2. At 600° F this alloy had a yield strength and ultimate strength about 20 percent higher than those of EM22 alloy and time-deformation curves developed for these two alloys at 600° F and at 1300-, 2000-, and 2500-psi stresses indicate that the creep resistance of the recommended alloy is substantially better. Forging and hot-rolling tests indicated that the hot-working characteristics of the new alloy would be reasonably satisfactory but that the alloy would be slightly more difficult to hot-work than EM22.

3. Considerable progress was made on correlating the composition and structure with the creep properties of the alloy. Although cerium was necessary to provide high tensile properties at 600° F, manganese appeared to be the more useful in imparting high resistance to creep in the magnesium-cerium-manganese ternary alloys at 600° F. Only those alloy constituents which were in solution appeared to be effective in improving the creep resistance of the material. It was found that with 0 percent cerium good creep properties could be obtained only by quenching from the solution-heat-treating temperature, but with 2 percent cerium good creep resistance could be obtained by air-cooling from the heat-treating temperature.

4. Substantial differences in creep resistance were produced as a result of differences in heat treatment, composition, or fabricating technique, or as a result of uncontrolled differences from heat to heat of similar compositions and from specimen to specimen from the same heat of material. For the most part, metallographic examination at magnifications up to 500X did not reveal the structural differences which must necessarily account for such differences in creep resistance. The X-ray diffraction and electron-microscope examinations showed that the structure of the alloys is quite complex. In general, fine particles as revealed by diffused diffraction lines were generally associated with good creep resistance.

5. Alpha and beta manganese as well as one unknown constituent were noted. There was some evidence that coarse particles of another phase, tentatively identified as the magnesium-cerium compound Mg_9Ce, had a slightly harmful effect on creep resistance.

Battelle Memorial Institute
Columbus, Ohio, July 18, 1949

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TABLE 1.- EFFECT OF MANGANESE ON TENSILE PROPERTIES OF EXTRUDED MAGNESIUM-CERIUM ALLOYS AT ROOM TEMPERATURE AND 600° F

Heat	Mn (percent)	Room temperature (1)			600° F (2)		
		Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)
2-percent-cerium alloys							
A5107	0	17,575	28,500	----	4300	7,275	87
A4970	.81	26,650	32,750	7.4	6100	9,475	115
A5270	.89	20,625	29,625	14.8	5900	8,550	128
A4971	1.24	28,400	33,250	5.5	7200	9,850	95
A4972	1.55	25,350	31,450	5.5	7150	9,325	81
A4975	1.90	27,250	33,000	7.2	7400	9,950	116
4-percent-cerium alloys							
A4847	0	29,100	32,350	5.7	4925	10,125	129
A4846	.62	26,175	30,850	6.5	6150	10,400	126
A4845	1.03	25,250	30,700	5.5	6575	10,675	125
A4844	1.38	24,850	30,250	3.5	6700	10,800	129
A4843	1.66	27,450	32,000	5.2	7025	11,300	100

[1]Tested in heat-treated and aged condition.
[2]Tested in heat-treated, aged, and stabilized condition.

TABLE 2.- EFFECT OF VARIOUS HEAT TREATMENTS AND OF CERIUM ON TENSILE AND CREEP PROPERTIES OF MANGANESE-MAGNESIUM EXTRUDED ALLOYS

Heat	Analysis		Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)			Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A4993	0	1.80	HTA	70	27,000	30,450	-----	----	---	-----	-------	-----	------	-----
			HTAS	600	3,400	4,400	86.0	63.0	244	0.041	0.0046	0.680	7.65	0.010
			HTQAS	600	------	------	-----	----	607	.042	.0003	.090	.281	.044
A5257	0	1.84	HTA	70	30,200	35,000	2.5	2.4	---	-----	-------	-----	------	-----
			HTQA	70	23,500	33,750	3.0	3.6	---	-----	-------	-----	------	-----
			HTAS	600	3,175	4,000	92.0	59.0	97	.052	.012	-----	4.10	.030
			HTQAS	600	4,675	5,400	47.0	42.7	553	.047	.00046	.114	[c]2.6	(d)
A5258	.20	1.94	HTA	70	24,900	27,250	1.5	1.7	---	-----	-------	-----	------	-----
			HTAS	600	5,150	8,300	86.5	67.9	566	.043	.0004	.110	[c]2.6	(d)
A5109	.41	1.65	HTA	70	23,900	31,000	[e]3.0	[e]3.1	---	-----	-------	-----	------	-----
			HTAS	600	6,075	9,200	46.0	58.8	599	.046	.0020	.301	1.48	.040
			HTQAS	600	------	------	-----	----	594	.041	.0040	2.92	5.42	.040
			Ann.	600	------	------	-----	----	56	.049	.077	-----	5.71	.050
A5259	.73	1.86	HTA	70	26,625	32,100	3.5	3.9	---	-----	-------	-----	------	-----
			HTAS	600	6,275	8,750	79.2	60.1	336	.044	.0022	.230	.502	.044
A4981	.75	1.56	HTA	70	17,650	28,000	11.7	12.3	---	-----	-------	-----	------	-----
			HTAS	600	5,575	7,900	105.0	83.4	335	.044	.012	1.60	6.88	.070
			HTAS	600	------	------	-----	----	217	.038	.003	1.90	2.48	.050
			Ann.	600	------	------	-----	----	56	.086	.130	-----	12.87	.010
A5110	1.34	1.56	HTA	70	29,900	35,375	5.5	7.5	---	-----	-------	-----	------	-----
			HTAS	600	7,275	10,650	86.0	79.7	597	.041	.0014	.303	1.05	.050
			HTQAS	600	------	------	-----	----	599	.043	.001	.375	.952	.034
			Ann.	600	------	------	-----	----	152	.044	.057	7.500	9.92	.070
A5260	1.39	1.94	HTA	70	31,500	35,175	7.0	7.3	---	-----	-------	-----	------	-----
			HTAS	600	7,100	9,750	100.0	74.2	609	.046	.0019	.285	1.89	.030
A4975	2.41	1.90	HTA	70	27,250	33,000	7.2	10.6	---	-----	-------	-----	------	-----
			HTAS	600	7,400	9,950	116.0	83.2	621	.049	.0008	.294	.714	.027
			HTQAS	600	------	------	-----	----	601	.050	.0035	.500	3.04	-----
			Ann.	600	------	------	-----	----	51	.055	.175	-----	11.04	.040
A4974	4.31	1.77	HTA	70	31,900	36,150	4.0	5.8	---	-----	-------	-----	------	-----
			HTAS	600	7,725	10,500	91.7	84.5	551	.043	.0034	.520	1.96	.050
			HTQAS	600	------	------	-----	----	602	.041	.0006	.300	.675	.032
			Ann.	600	------	------	-----	----	102	.046	.060	-----	6.95	.050
A4973	6.01	1.81	HTA	70	27,500	37,500	2.8	3.3	---	-----	-------	-----	------	-----
			HTAS	600	7,750	10,850	122.5	89.7	360	.042	.0020	.504	1.53	.045
			HTQAS	600	------	------	-----	----	594	.046	.00043	.230	.445	.045
			Ann.	600	------	------	-----	----	126	.040	.077	9.000	9.96	.040
A5277	5.33	1.75	HTA	70	35,250	35,800	3.2	3.5	---	-----	-------	-----	------	-----
			HTAS	600	8,300	11,700	125.5	92.3	458	.050	.010	1.130	4.80	.040
			HTQAS	600	------	------	-----	----	534	.040	.00075	.550	.899	.035

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS same as HTA and stabilized 24 hr at 650° F following the aging treatment.
HTQAS aged and stabilized as above except water-quenched from the solution-heat-treating temperature.
Ann. furnace-cooled from solution-heat-treating temperature.

[b]Each tensile property is the average of two test results unless otherwise specified.

[c]Measured after rupture.

[d]Specimen broke.

[e]One test value.

TABLE 3.- ANALYSES, HEAT TREATMENTS, METHODS OF FABRICATION, AND TENSILE AND CREEP PROPERTIES OF MAGNESIUM-CERIUM ALLOYS

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A4993	----	1.80	-------	Extrusion	HTA	70	27,000	30,450	-----	----	-----	-----	-------	-----	------	-----
					HTAS	600	3,400	4,400	86.0	63.0	244	0.041	0.0046	0.680	7.65	0.010
					HTQAS	600	------	------	-----	----	607	.042	.0003	.090	.281	.044
A5257	----	1.84	-------	Extrusion	HTA	70	30,200	35,000	2.5	2.4	-----	-----	-------	-----	------	-----
					HTQA	70	23,500	33,750	3.0	3.6	-----	-----	-------	-----	------	-----
					HTAS	600	3,175	4,000	92.0	59.0	96.8	.052	.012	-----	4.10	.030
					HTQAS	600	4,675	5,400	47.0	42.7	553.2	.047	.00046	.114	[c]2.6	(d)
A5258	0.20	1.94	-------	Extrusion	HTA	70	24,900	27,250	1.5	1.7	-----	-----	-------	-----	------	-----
					HTAS	600	5,150	8,300	86.5	67.9	566	.043	.0004	.110	[c]2.6	(d)
A5109	.41	1.65	-------	Extrusion	HTA	70	23,900	31,000	[e]3.0	[e]3.1	-----	-----	-------	-----	------	-----
					HTAS	600	6,075	9,200	46.0	58.8	599	.046	.0020	.301	1.48	.040
					HTQAS	600	------	------	-----	----	594	.041	.0040	2.92	5.42	.040
					Ann.	600	------	------	-----	----	56	.049	.077	-----	5.71	.050
A5259	.73	1.86	-------	Extrusion	HTA	70	26,625	32,100	3.5	3.9	-----	-----	-------	-----	------	-----
					HTAS	600	6,275	8,750	79.2	60.1	335.9	.044	.0022	.230	.502	.044
A4981	.75	1.56	-------	Extrusion	HTA	70	17,650	28,000	11.7	12.3	-----	-----	-------	-----	------	-----
					HTAS	600	5,575	7,900	105.0	83.4	335	.044	.012	1.60	6.88	.070
					HTAS	600	------	------	-----	----	217	.038	.003	1.9	2.48	.050
					Ann.	600	------	------	-----	----	56	.086	.130	-----	12.87	.010
A5110	1.34	1.56	-------	Extrusion	HTA	70	29,900	35,375	5.5	7.5	-----	-----	-------	-----	------	-----
					HTAS	600	7,275	10,650	86.0	79.7	597	.041	.0014	.303	1.05	.050
					HTQAS	600	------	------	-----	----	599	.043	.001	.375	.952	.034
					Ann.	600	------	------	-----	----	152	.044	.057	7.500	9.92	.070
A5260	1.39	1.94	-------	Extrusion	HTA	70	31,500	35,175	7.0	7.3	-----	-----	-------	-----	------	-----
					HTAS	600	7,100	9,750	100.0	74.2	608.8	.046	.0019	.285	1.89	.030
A5108	1.37	----	-------	Extrusion	HTA	70	17,450	27,150	9.5	12.1	-----	-----	-------	-----	------	-----
					HTAS	600	4,700	7,450	85.7	66.3	-----	-----	-------	-----	------	-----

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.

HTAS same as HTA and stabilized as follows:

Test temperature	Stabilization
400° F	24 hr at 500° F
500° F	24 hr at 575° F
600° F	24 hr at 650° F

HTQA same as HTA except quenched in cold water from solution-heat-treating temperature.

HTQAS same as HTAS except quenched in cold water from solution-heat-treating temperature.

Ann. furnace-cooled from solution-heat-treating temperature.

[b]Each tensile property is the average of two test results unless otherwise specified.

[c]Measured after rupture.

[d]Specimen broke.

[e]Value for one test bar.

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TABLE 3.- ANALYSES, HEAT TREATMENTS, METHODS OF FABRICATION, AND TENSILE AND CREEP PROPERTIES OF MAGNESIUM-CERIUM ALLOYS - Continued

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A5107	2.33	----	-------	Extrusion	HTA	70	17,575	28,500	-----	-----	------	-----	-------	-----	-----	-----
					HTAS	600	4,300	7,275	140.0	86.6	52	0.043	0.170	-----	8.68	(f)
					HTQAS	600	-------	-------	-----	-----	52	.050	.106	-----	8.32	0.040
					Ann.	600	-------	-------	-----	-----	36	.056	(g)	-----	-----	-----
A4970	2.24	0.81	-------	Extrusion	HTA	70	26,650	32,750	7.4	9.8	------	-----	-------	-----	-----	-----
					HTAS	600	6,100	9,475	115.0	78.2	150.0	.043	.0020	0.273	.330	.033
A5270	1.92	.89	-------	Extrusion	HTA	70	20,625	29,625	14.8	15.7	------	-----	-------	-----	-----	-----
					HTAS	600	5,900	8,550	127.7	82.6	------	-----	-------	-----	-----	-----
A4971	[h]2.00	1.24	-------	Extrusion	HTA	70	28,400	33,250	5.5	8.9	------	-----	-------	-----	-----	-----
					HTAS	600	7,200	9,850	95.0	72.9	144.0	.047	.0020	.385	.433	.039
A4972	2.45	1.55	-------	Extrusion	HTA	70	25,350	31,450	5.5	6.8	------	-----	-------	-----	-----	-----
					HTAS	600	7,150	9,325	81.0	62.6	146.0	.043	.0011	.300	.336	.032
A5261	1.95	1.93	-------	Extrusion	HTA	70	34,850	36,450	5.0	5.8	------	-----	-------	-----	-----	-----
					HTAS	600	7,400	10,275	103.5	79.6	605.5	.039	.0014	.210	.934	.040
A5262	2.14	1.86	-------	Extrusion	HTA	70	33,500	35,800	4.5	5.8	------	-----	-------	-----	-----	-----
					HTA	300	[e]12,600	[e]20,000	[e]22.0	[e]25.2	------	-----	-------	-----	-----	-----
					HTAS	400	[e]9,800	[e]16,700	[e]26.0	[e]40.3	------	-----	-------	-----	-----	-----
					HTAS	500	[e]8,050	[e]13,700	[e]50.0	[e]57.8	------	-----	-------	-----	-----	-----
					HTAS	600	7,275	10,100	88.5	80.1	[i]503.0	.021	.00015	.073	.145	.027
					HTAS	600	-------	-------	-----	-----	500.0	.035	.00055	.152	.412	.034
					HTAS	600	-------	-------	-----	-----	[j]332.0	.050	.00080	1.150	5.140	.080
A5263	2.25	1.85	-------	Extrusion	HTA	70	34,425	36,300	5.5	7.9	------	-----	-------	-----	-----	-----
					HTA	300	16,500	20,500	24.0	36.3	------	-----	-------	-----	-----	-----
					HTAS	400	11,100	16,800	26.0	50.0	------	-----	-------	-----	-----	-----
					HTAS	500	8,625	14,225	42.0	62.8	------	-----	-------	-----	-----	-----
					HTAS	600	7,200	10,200	102.5	76.7	597.1	.041	.0017	.260	1.14	.030

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.

HTAS same as HTA and stabilized as follows:

Test temperature	Stabilization
400° F	24 hr at 500° F
500° F	24 hr at 575° F
600° F	24 hr at 650° F

HTQA same as HTA except quenched in cold water from solution-heat-treating temperature.

HTQAS same as HTAS except quenched in cold water from solution-heat-treating temperature.

Ann. furnace-cooled from solution-heat-treating temperature.

[b]Each tensile property is the average of two test results unless otherwise specified.

[e]Value for one test bar.

[f]Final reading not obtainable.

[g]Creep rate very high; test discontinued.

[h]Intended composition.

[i]At 1300-psi stress.

[j]At 2500-psi stress.

TABLE 3.- ANALYSES, HEAT TREATMENTS, METHODS OF FABRICATION, AND TENSILE AND CREEP PROPERTIES OF MAGNESIUM-CERIUM ALLOYS - Continued

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A4975	2.41	1.90	------	Extrusion	HTA	70	27,250	33,000	7.2	10.6	-----	-----	-------	-----	------	-----
					HTAS[k]	600	7,400	9,950	116.0	83.2	621	0.049	0.0008	0.294	0.714	0.027
					HTQAS	600	------	------	-----	----	601	.050	.0035	.500	3.04	-----
					Ann.	600	------	------	-----	----	51	.055	.175	-----	11.04	.040
A4975	2.41	1.90	------	Sand-cast	HTAS[l]	600	6,550	9,075	72.0	55.3	307	.041	.00015	.080	.133	.048
					HTAS	600	------	------	-----	----	304	.044	.00007	.132	[m].150	-----
A4975	2.41	1.90	------	Sand-cast	HTAS[n]	600	------	------	-----	----	288	.041	.00030	.122	.178	.035
					HTAS	600	------	------	-----	----	312	.046	.00012	.072	.104	.039
A4975	2.41	1.90	------	0.060-inch rolled sheet[o]	HTA	70	15,250	26,550	9.8	----	-----	-----	-------	-----	------	-----
					HTAS	600	------	8,325	51.5	----	150.0	.024	.0055	.750	.982	.026
					HTAS	600	------	------	-----	----	150.3	.029	.0165	3.50	4.95	Nil
A4975	2.41	1.90	------	0.060-inch rolled sheet[p]	HTA	70	14,125	26,700	8.0	----	-----	-----	-------	-----	-----	-----
					HTAS	600	------	7,125	40.0	----	211.0	.023	.0065	.812	1.89	.010
					HTAS	600	------	------	-----	----	208.7	.023	.012	2.27	7.08	.020
A4847	[h]4.00	----	------	Extrusion	HTA	70	29,100	32,350	5.7	7.6	-----	-----	-------	-----	------	-----
					HTAS	600	4,925	10,125	128.7	88.4	24.0	.043	(g)	-----	------	-----
A4843	4.34	1.66	------	Extrusion	HTA	70	27,450	32,000	5.2	5.7	-----	-----	-------	-----	------	-----
					HTAS	600	7,025	11,300	100.0	73.6	145.9	.040	.0425	4.00	5.67	.040
					HTAS	600	------	------	-----	----	239.0	.043	.0100	1.30	2.58	.040
A5054	[h]4.00	1.80	------	Extrusion	HTA	70	35,950	38,150	3.3	4.9	-----	-----	-------	-----	------	-----
					HTAS	600	8,325	11,450	109.0	85.8	407.9	.045	.0052	.764	7.08	.040

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.

HTAS same as HTA and stabilized as follows:

Test temperature	Stabilization
400° F	24 hr at 500° F
500° F	24 hr at 575° F
600° F	24 hr at 650° F

HTQA same as HTA except quenched in cold water from solution-heat-treating temperature.

HTQAS same as HTAS except quenched in cold water from solution-heat-treating temperature.

Ann. furnace-cooled from solution-heat-treating temperature.

[b]Each tensile property is the average of two test results unless otherwise specified.

[g]Creep rate very high; test discontinued.

[h]Intended composition.

[k]Grain size, 0.003 in.

[l]Grain size, 0.05-0.06 in.

[m]Estimated value.

[n]Grain size, 0.02 in.

[o]Parallel to direction of rolling.

[p]Transverse to direction of rolling.

TABLE 3.- ANALYSES, HEAT TREATMENTS, METHODS OF FABRICATION, AND TENSILE AND CREEP PROPERTIES OF MAGNESIUM-CERIUM ALLOYS - Continued

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A5055	4.22	1.73	--------	Extrusion	HTA	70	[e]36,175	37,300	3.5	5.7	-----	-----	--------	-----	-----	-----
A5056	[h]4.00	1.71	--------	Extrusion	HTA	70	34,500	36,400	3.8	4.5	-----	-----	--------	-----	-----	-----
A4974	4.31	1.77	--------	Extrusion	HTA	70	31,900	36,150	4.0	5.8	-----	-----	--------	-----	-----	-----
					HTAS	600	7,725	10,500	91.7	84.5	551.0	0.043	0.0034	0.520	1.96	0.050
					HTQAS	600	-------	-------	--------	--------	602.0	.041	.0006	.300	.675	.032
					Ann.	600	-------	-------	--------	--------	102.0	.046	.060	-----	6.95	.050
A4973	6.01	1.81	--------	Extrusion	HTA	70	27,500	37,500	2.8	3.3	-----	-----	--------	-----	-----	-----
					HTAS	600	7,750	10,850	122.5	89.7	360.0	.042	.0020	.504	1.53	.045
					HTQAS	600	-------	-------	--------	--------	594.0	.046	.00043	.230	.445	.045
					Ann.	600	-------	-------	--------	--------	126.0	.040	.077	9.00	9.96	.040
A5277	5.33	1.75	--------	Extrusion	HTA	70	35,250	35,800	3.2	3.5	-----	-----	--------	-----	-----	-----
					HTAS	600	8,300	11,700	125.5	92.3	458.0	.050	.010	1.130	4.800	.040
					HTQAS	600	-------	-------	--------	--------	533.7	.040	.00075	.550	.899	.035
A5275	[h]2.00	[h].70	[h]0.25 Al	Extrusion	HTA	70	25,300	31,000	8.0	9.0	-----	-----	--------	-----	-----	-----
					HTAS	600	5,525	9,750	85.0	70.3	-----	-----	--------	-----	-----	-----
A4980	[h]2.00	[h]1.70	[h].50 Cd	Extrusion	HTA	70	[e]26,700	31,625	9.5	10.5	-----	-----	--------	-----	-----	-----
					HTAS	600	7,275	9,400	50.0	43.4	167.0	.044	.0015	.330	.395	.026
A4976	2.23	1.90	.31 Ni	Extrusion	HTA[q]	70	[e]26,200	[e]32,250	[e]7.0	[e]7.3	-----	-----	--------	-----	-----	-----
					HTA	70	30,700	32,250	1.5	1.1	-----	-----	--------	-----	-----	-----
					HTAS	600	9,375	12,700	84.2	67.5	287.0	.041	.00025	.110	.167	.043
					HTAS[q]	600	[e]8,700	[e]12,500	[e]32.5	84.0	284.3	-----	.0015	.262	.635	-----
A4976	2.23	1.90	.31 Ni	Sand-cast	HTAS	600	6,500	9,400	3.0-54.0	2.8-48.4	336.0	.039	.00025	.083	.182	.048
					HTAS	600	-------	-------	--------	--------	312.0	.041	.00032	.095	.160	.044

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.

HTAS same as HTA and stabilized as follows:

Test temperature	Stabilization
400° F	24 hr at 500° F
500° F	24 hr at 575° F
600° F	24 hr at 650° F

HTQA same as HTA except quenched in cold water from solution-heat-treating temperature.

HTQAS same as HTAS except quenched in cold water from solution-heat-treating temperature.

Ann. furnace-cooled from solution-heat-treating temperature.

[b]Each tensile property is the average of two test results unless otherwise specified.

[e]Value for one test bar.

[h]Intended composition.

[q]Solution-heat-treated at 1000° F.

TABLE 3.- ANALYSES, HEAT TREATMENTS, METHODS OF FABRICATION, AND TENSILE AND CREEP PROPERTIES OF MAGNESIUM-CERIUM ALLOYS - Continued

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A5269	2.04	0.92	[h]0.20 Ni	Extrusion	HTA	70	31,750	34,400	3.0	3.9	-----	-----	-------	-----	-----	-----
					HTAS	600	7,700	11,300	78.0	63.2	-----	-----	-------	-----	-----	-----
A5454	[h]2.00	[h]1.70	[h].20 Ni	Extrusion	HTA	70	28,375	30,000	1.8	1.1	-----	-----	-------	-----	-----	-----
					HTA	300	15,750	23,500	19.0	23.0	-----	-----	-------	-----	-----	-----
					HTAS	400	10,800	18,125	27.0	35.8	-----	-----	-------	-----	-----	-----
					HTAS	600	8,700	12,200	97.7	71.7	435.3	0.040	0.0002	0.088	0.181	0.044
A5465	[h]2.00	[h]1.70	[h].20 Ni	Extrusion	HTA[q]	70	18,750	29,500	8.0	8.5	-----	-----	-------	-----	-----	-----
					HTA	70	27,950	29,300	1.3	1.0	-----	-----	-------	-----	-----	-----
					HTAS	500	12,150	17,900	31.0	41.5	-----	-----	-------	-----	-----	-----
					HTAS	600	9,000	12,600	41.5	36.5	600.4	.046	.0002	.132	.232	.037
					HTAS[q]	600	7,650	10,850	105.0	61.5	-----	-----	-------	-----	-----	-----
A5628	1.78	1.54	.18 Ni	Forging	HTA	70	12,575	27,000	9.5	7.6	-----	-----	-------	-----	-----	-----
					HTAS	600	6,475	9,225	104.5	76.7	-----	-----	-------	-----	-----	-----
A5629	1.78	[h]1.70	.17 Ni	Forging	HTA	70	12,950	27,250	8.7	9.2	-----	-----	-------	-----	-----	-----
					HTAS	600	6,625	9,575	97.5	70.6	-----	-----	-------	-----	-----	-----
A5460	2.08	1.79	[h].50 Sr	Extrusion	HTA	70	25,675	30,000	5.0	2.6	-----	-----	-------	-----	-----	-----
					HTAS	600	6,550	9,750	113.5	84.2	-----	-----	-------	-----	-----	-----
A5272	[h]2.00	[h].70	[h].10 Te	Extrusion	HTA	70	23,250	30,000	11.0	11.8	-----	-----	-------	-----	-----	-----
					HTAS	600	6,200	8,650	133.5	75.6	-----	-----	-------	-----	-----	-----

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.

HTAS same as HTA and stabilized as follows:

Test temperature	Stabilization
400° F	24 hr at 500° F
500° F	24 hr at 575° F
600° F	24 hr at 650° F

HTQA same as HTA except quenched in cold water from solution-heat-treating temperature.

HTQAS same as HTAS except quenched in cold water from solution-heat-treating temperature.

Ann. furnace-cooled from solution-heat-treating temperature.

[b]Each tensile property is the average of two test results unless otherwise specified.

[h]Intended composition.

[q]Solution-heat-treated at 1000° F.

TABLE 3.- ANALYSES, HEAT TREATMENTS, METHODS OF FABRICATION, AND TENSILE AND CREEP PROPERTIES OF MAGNESIUM-CERIUM ALLOYS - Continued

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A5457	2.03	1.91	0.20 Ni, [h]0.25 Ag	Extrusion	HTA	70	28,250	28,800	1.3	0.9	-----	-----	-------	-----	-----	-----
					HTAS	600	8,600	12,000	80.0	57.3	435.1	0.042	0.00025	0.126	0.218	0.038
A5458	[h]2.00	[h]1.70	.20 Ni, [h].05 Al	Extrusion	HTA	70	30,000	31,500	2.5	2.3	-----	-----	-------	-----	-----	-----
					HTAS	600	8,425	11,900	93.2	71.8	-----	-----	-------	-----	-----	-----
A5459	2.09	1.72	.24 Ni, .14 Al	Extrusion	HTA	70	27,650	31,750	10.3	13.1	-----	-----	-------	-----	-----	-----
					HTAS	600	6,700	10,000	126.2	86.5	481.0	.042	.0009	.255	.516	.041
A5276	[h]2.00	[h].70	.20 Ni, [h].25 Al	Extrusion	HTA	70	25,400	30,000	6.5	6.9	-----	-----	-------	-----	-----	-----
					HTAS	600	6,525	9,275	107.5	68.8	-----	-----	-------	-----	-----	-----
A4978	2.15	1.90	.20 Ni, [h].50 Cd	Extrusion	HTA	70	-------	[e]28,000	-----	----	-----	-----	-------	-----	-----	-----
					HTAS	600	9,650	12,800	62.5	47.1	290.0	.041	.00038	[m].120	[m].19	.046
A5466	[h]2.00	[h]1.70	.20 Ni, [h].20 Co	Extrusion	HTA	70	29,375	31,625	1.5	3.3	-----	-----	-------	-----	-----	-----
					HTAS	600	8,800	12,100	96.3	73.4	-----	-----	-------	-----	-----	-----
A5463	1.88	1.79	.20 Ni, [h].05 Mo	Extrusion	HTA	70	27,775	28,550	1.0	.6	-----	-----	-------	-----	-----	-----
					HTAS	600	9,000	12,300	74.0	58.8	-----	-----	-------	-----	-----	-----
A5274	2.00	.89	.20 Ni, [h].25 Sr	Extrusion	HTA	70	[e]30,000	[e]30,000	[e]1.0	[e].4	-----	-----	-------	-----	-----	-----
					HTAS	600	8,050	12,200	43.8	41.6	-----	-----	-------	-----	-----	-----
A5461	[h]2.00	[h]1.70	.20 Ni, [h].50 Sr	Extrusion	HTA	70	27,250	28,125	1.0	.6	-----	-----	-------	-----	-----	-----
					HTAS	600	9,350	12,950	33.5	29.8	453.8	.045	[r].00052	.125	.275	.038
A5273	[h]2.00	[h].70	.20 Ni, [h].10 Te	Extrusion	HTA	70	32,625	34,625	2.5	2.7	-----	-----	-------	-----	-----	-----
					HTAS	600	8,125	11,500	94.0	75.9	-----	-----	-------	-----	-----	-----
A5456	[h]2.00	[h]1.70	.20 Ni, [h].10 Ti	Extrusion	HTA	70	28,250	32,750	6.8	9.0	-----	-----	-------	-----	-----	-----
					HTAS	600	7,500	10,300	121.2	78.2	-----	-----	-------	-----	-----	-----

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS same as HTA and stabilized as follows:

Test temperature	Stabilization
400° F	24 hr at 500° F
500° F	24 hr at 575° F
600° F	24 hr at 650° F

HTQA same as HTA except quenched in cold water from solution-heat-treating temperature.
HTQAS same as HTAS except quenched in cold water from solution-heat-treating temperature.
Ann. furnace-cooled from solution-heat-treating temperature.
[b]Each tensile property is the average of two test results unless otherwise specified.
[e]Value for one test bar.
[h]Intended composition.
[m]Estimated value.
[r]Creep rate was 0.00052 percent/hr from 25 to 360 hr and 0.00025 percent/hr or less from 360 to 450 hr. Time at this decreasing rate was insufficient to determine a minimum creep rate accurately.

TABLE 3.- ANALYSES, HEAT TREATMENTS, METHODS OF FABRICATION, AND TENSILE AND CREEP PROPERTIES OF MAGNESIUM-CERIUM ALLOYS - Concluded

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A5266	1.98	1.90	0.20 Ni, [h]0.02 W	Extrusion	HTA[s]	70	26,850	27,750	3.0	3.7	-----	-----	-------	-----	-----	-----
					HTAS	600	6,825	10,450	101.3	74.7	-----	-----	-------	-----	-----	-----
A5267	[h]2.0	[h]1.70	.20 Ni, [h].02 W	Extrusion	HTA	70	-------	27,750	1.0	.9	-----	-----	-------	-----	-----	-----
					HTAS	600	8,950	12,000	117.5	75.0	-----	-----	-------	-----	-----	-----
A5271	2.03	.95	.20 Ni, [h].02 W	Extrusion	HTA	70	[e]27,500	30,250	[e]1.5	[e].8	-----	-----	-------	-----	-----	-----
					HTAS	600	8,675	12,300	36.0-85.0	50.3	-----	-----	-------	-----	-----	-----
A4979	[h]2.00	[h]1.70	.20 Ni, [h].50 Cd, .02 W	Extrusion	HTA	70	-------	30,425	1.0	.8	-----	-----	-------	-----	-----	-----
					HTAS	600	9,900	12,900	69.0	50.7	313.0	0.041	0.00030	0.124	0.181	0.037
A5467	2.10	1.87	.20 Ni, [h].50 Sr, .25 Ag	Extrusion	HTA	70	-------	25,175	1.0	[e].4	-----	-----	-------	-----	-----	-----
					HTAS	600	8,800	12,400	17.2	15.2	591.7	.049	.0001	.108	.175	.042
A5474	[h]2.00	[h]1.70	.20 Ni, [h].02 W, .25 Ag	Extrusion	HTA	70	-------	24,175	1.0	.4	-----	-----	-------	-----	-----	-----
					HTAS	600	8,600	12,000	19.5-55.0	31.0	528.6	.045	.00025	.110	.242	.046
A5468	[h]2.00	[h]1.70	.20 Ni, [h].75 Zr, .25 Ag	Extrusion	HTA	70	[e]27,500	27,500	1.0	.4	-----	-----	-------	-----	-----	-----
					HTAS	600	8,700	11,750	51.5	40.8	-----	-----	-------	-----	-----	-----
A5475	[h]2.00	[h]1.70	.75 Zr, [h].05 Be, .25 Ag	Extrusion	HTA	70	26,550	30,800	11.5	14.1	-----	-----	-------	-----	-----	-----
					HTAS	600	6,575	9,175	119.0	78.6	-----	-----	-------	-----	-----	-----
A4851	-----	[h].20	8.5 Al, [h].60 Zn,	Extrusion	HTA[t]	70	38,875	49,500	3.8	3.7	-----	-----	-------	-----	-----	-----
					HTA[t]	600	5,050	7,950	150.0	95.0	20	.062	(g)	-----	-----	-----
A5268	-----	[h]1.70	.20 Ni, [h].02 W	Extrusion	HTA	70	27,950	35,375	3.5	4.1	-----	-----	-------	-----	-----	-----
					HTAS	600	4,625	5,725	95.2	73.2	-----	-----	-------	-----	-----	-----

[a]HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS same as HTA and stabilized as follows:

Test temperature	Stabilization
400° F	24 hr at 500° F
500° F	24 hr at 575° F
600° F	24 hr at 650° F

HTQA same as HTA except quenched in cold water from solution-heat-treating temperature.
HTQAS same as HTAS except quenched in cold water from solution-heat-treating temperature.
Ann. furnace-cooled from solution-heat-treating temperature.
[b]Each tensile property is the average of two test results unless otherwise specified.
[c]Value for one test bar.
[g]Creep rate very high; test discontinued.
[h]Intended composition.
[s]Damaged during extrusion process.
[t]Heated 4 hr at 750° F, air-cooled, and aged 24 hr at 350° F.

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TABLE 4.- EXPERIMENTAL ROLLING TESTS ON SOME MAGNESIUM-CERIUM ALLOYS

Heat	Analysis			Original thickness (in.)	Thickness after scalping (in.)	Hot-rolling				Remarks
	Ce (percent)	Mn (percent)	Others (percent)			Temperature (°F)	Number of reheatings	Number of passes	Finished size (in.)	
A4843	4.43	1.66	----------	1.50	1.25	1000	3	16	0.230	Cracked on 16th pass
A4844	4.39	1.38	----------	1.50	1.30	1000	8	25	.060	Rolled satisfactorily
A4845	4.50	1.03	----------	1.50	1.30	1000	8	24	.060	Rolled satisfactorily
A4846	4.50	.62	----------	1.50	1.26	1000	3	16	.235	Cracked on 16th pass
A4848	6.27	1.60	----------	1.50	1.26	1000	0	2	[a]1.000	Cracked severely on second pass; rolling discontinued
A4849	2.47	1.68	----------	1.50	1.30	1000	9	25	.060	Rolled satisfactorily
A4850	6.00	1.70	0.50 Al	1.50	1.30	1000	7	22	.098	Cracked on 15th and 18th passes
A4895	3.95	1.40	----------	-----	1.81	1000	7	22	.115	$3\frac{1}{8}$-in.-square billet forged to $1\frac{13}{16}$ in. for rolling; rolled satisfactorily
A4896	[b]4.00	[b]1.35	----------	-----	1.81	1000	7	22	.115	$3\frac{1}{8}$-in.-square billet forged to $1\frac{13}{16}$ in. for rolling; rolled satisfactorily
A4897	4.19	1.04	----------	-----	1.81	1000	7	22	.115	$3\frac{1}{8}$-in.-square billet forged to $1\frac{13}{16}$ in. for rolling; slight cracking
A4975	2.41	1.90	----------	1.50	----	1000	11	30	.073	3-in.-diam. billet forged to $1\frac{1}{2}$ by 4 in. for rolling; cold-rolled to 0.060 in.; some cracking occurred during cold-rolling
A4981	.75	1.56	----------	1.50	----	1000	11	29	.073	3-in.-diam. billet forged to $1\frac{1}{2}$ by 4 in. for rolling; cold-rolled to 0.060 in.
A4993	0	1.80	----------	1.50	----	800	9	28	.076	3-in.-diam. billet forged to $1\frac{1}{2}$ by 4 in. for rolling; cold-rolled to 0.060 in.; some cracking occurred during cold-rolling
A5271	2.03	.95	[b].02 W, [b].20 Ni,	1.50	1.40	900	0	1	------	Cracked severely on first pass
A5272	[b]2.00	[b].70	.10 Te	1.50	1.05	900	6	21	.097	Cold-rolled to 0.066 in. after annealing 1 hr at 900° F; some edge cracking
A5273	[b]2.00	[b].70	[b].20 Ni, [b].10 Te	1.50	1.22	900	0	1	------	Cracked on first pass
A5274	2.00	.89	[b].20 Ni, [b].25 Sr,	1.50	1.06	900	0	1	------	Cracked on first pass
A5275	[b]2.00	[b].70	.25 Al	1.50	1.22	900	7	24	.096	Cold-rolled to 0.066 in. after annealing 1 hr at 900° F; some edge cracking
A5276	[b]2.00	[b].70	[b].20 Ni, [b].25 Al	1.50	1.43	900	7	24	.095	Cold-rolled to 0.066 in. after annealing 1 hr at 900° F; some edge cracking
A5457	[b]2.00	[b]1.70	[b].20 Ni, [b].25 Ag	[c].975	----	850	5	16	.196	Cracking started on 12th pass
				[c].975	----	950	5	16	.185	Rolled better than at the lower temperature
A5458	[b]2.00	[b]1.70	[b].20 Ni, [b].05 Al	[c].975	----	850	5	16	.196	Slight edge cracking on last pass
				[c].975	----	950	5	16	.185	No cracking; rolled better than at 850° F
A5459	2.09	1.72	.14 Al, .24 Ni	[c].975	----	850	5	16	.196	Started edge cracking on 12th pass
				[c].975	----	950	0	1	------	Cracked severely on first pass
A5460	2.08	1.79	[b].50 Sr	[c].975	----	850	5	16	.195	Very slight edge cracking
				[c].975	----	950	5	16	.186	Very slight edge cracking
A5461	[b]2.00	[b]1.70	[b].20 Ni, [b].50 Sr	[c].975	----	850	5	16	.190	Considerable edge cracking; rolled satisfactorily
				[c].975	----	950	5	16	.203	
A5465	[b]2.00	[b]1.70	[b].20 Ni	[c].975	----	850	5	16	.194	Slight edge cracking
				[c].975	----	950	5	16	.188	Very slight edge cracking
A5467	2.10	1.87	[b].50 Sr, [b].20 Ni, [b].25 Ag	[c].975	----	850	5	16	.194	Very slight edge cracking; rolled exceptionally well
				[c].975	----	950	5	16	.188	Rolled very readily
A5474	[b]2.00	[b]1.70	.20 Ni, [b].02 W, [b].25 Ag	[c].975	----	950	5	16	.190	Slight edge cracking
A5462	[b]2.00	[b]1.70	----------	1.250	----	925	9	24	.090	Hot-rolled satisfactorily; cold-rolled to 0.082 in. after annealing 1 hr at 900° F
A5464	[b]2.00	[b]1.70	[b].20 Ni, [b].50 Zr, [b].01 Be	1.250	----	925	9	24	.090	Hot-rolled satisfactorily; cold-rolled to 0.081 in. after annealing 1 hr at 900° F
A5600	2.05	1.75	.25 Ni	1.500	----	925	10	26	.090	Hot-rolled satisfactorily; cold-rolled to 0.074 in. after annealing 1 hr at 900° F

[a]Approximation.
[b]Intended composition.
[c]Plates were not scalped prior to rolling.

TABLE 5.- FORGING TESTS OF FIVE MAGNESIUM-CERIUM-MANGANESE ALLOYS

Heat	Analysis			Soaking temperature (°F) (a)	Forging temperature (°F)	Original dimensions	Finished dimensions (in.)	Remarks
	Ce (percent)	Mn (percent)	Ni (percent)					
A5264	[b]4.00	[b]1.70	-----	900	950	4-in.-diam. billet[b] [c]	$1\frac{3}{4}$ by $1\frac{3}{4}$ by 21	Some cracks and splitting occurred in the later stages of forging; no further work was done on the finished billet
A5600	[b]2.05	[b]1.75	[b]0.25	900	950	4-in.-diam. billet[c]	Broke	Ingots broke in the first stages of forging
A5601	[b]2.13	[b]1.92	[b].27	900	950	4-in.-diam. billet[c]	Broke	
A5628	1.78	1.54	0.18	900	950	8 by 5 by 5 in.[d]	2 by 2 by 25	Ingots cracked to some extent; however, by repeated heating and forging, they were reduced to the finished size. After they were forged, the billets were machined to a $1\frac{1}{4}$-in. square, and then rolled to $\frac{7}{8}$-in. diam., at a temperature of 950° F, with no cracks occurring during rolling
A5629	1.78	[b]1.70	.17	900	950	8 by 5 by 5 in.[d]	2 by 2 by 25	

[a]Soaked overnight at the indicated temperature prior to forging.
[b]Intended composition.
[c]Water-cooled ingot.
[d]Chill-cast in gray-iron ingot mold.

TABLE 6.- EFFECT OF METHOD OF FABRICATION ON TENSILE AND CREEP PROPERTIES OF CERIUM-MANGANESE-MAGNESIUM ALLOYS

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A4849	2.47	1.68	-------	Extrusion	HTA	70	27,900	30,500	9.0	9.2	-----	-----	-------	-----	------	-----
					HTAS	600	6,500	10,500	100.0	79.0	144.5	0.045	0.0057	0.800	0.902	0.036
					HTAS	600	------	------	-----	----	313.0	.047	.00045	.255	.393	.032
				Sand-cast	HTA	70	5,050	8,750	35.0	45.9	-----	-----	-------	-----	------	-----
				$\frac{1}{4}$-in. rolled plate[c]	HTA	70	13,550	24,000	4.1	----	-----	-----	-------	-----	------	-----
A4975	2.41	1.90	-------	Extrusion	HTA	70	27,250	33,000	7.2	10.6	-----	-----	-------	-----	------	-----
					HTAS[d]	600	7,400	9,950	116.0	83.2	621	.049	.0008	.294	.714	.027
					HTQAS	600	------	------	-----	----	601	.050	.0035	.500	3.04	-----
					Ann.	600	------	------	-----	----	51	.055	.175	-----	11.04	.040
				Sand-cast	HTAS[e]	600	6,550	9,075	72.0	55.3	307	.041	.00015	.080	.133	.048
					HTAS	600	------	------	-----	----	304	.044	.00007	.132	[f].150	-----
				Sand-cast	HTAS[g]	600	------	------	-----	----	288	.041	.00030	.122	.178	.035
					HTAS	600	------	------	-----	----	312	.046	.00012	.072	.104	.039
				0.060-in. rolled sheet[h]	HTA	70	15,250	26,550	9.8	----	-----	-----	-------	-----	------	-----
					HTAS	600	------	8,325	51.5	----	150	.024	.0055	.750	.982	.026
					HTAS	600	------	------	-----	----	150	.029	.0165	3.50	4.95	-----
				0.060-in. rolled sheet[i]	HTA	70	14,125	26,700	8.0	----	-----	-----	-------	-----	------	-----
					HTAS	600	------	7,125	40.0	----	211	.023	.0065	.812	1.89	.010
					HTAS	600	------	------	-----	----	208.7	.023	.012	2.27	7.08	.020
A5462	[j]2.00	[j]1.70	-------	Extrusion	HTA	70	28,250	31,700	6.0	7.2	-----	-----	-------	-----	------	-----
					HTAS	600	6,700	9,300	85.0	54.2	434	.042	.00045	.186	.349	.034
				0.080-in. rolled sheet	HTA	70	15,000	26,650	10.5	----	-----	-----	-------	-----	------	-----
					HTAS	600	------	7,825	80.0	----	-----	-----	-------	-----	------	-----

[a] HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS same as HTA and stabilized 24 hr at 650° F following the aging treatment.
HTQAS aged and stabilized as above except water-quenched from the solution-heat-treating temperature.
Ann. furnace-cooled from solution-heat-treating temperature.

[b] Each tensile property is the average of two test results unless otherwise specified.

[c] Flaw.

[d] Grain size, 0.003 in.

[e] Grain size, 0.05-0.05 in.

[f] Estimated value.

[g] Grain size, 0.02 in.

[h] Parallel to direction of rolling.

[i] Transverse to direction of rolling.

[j] Intended composition.

TABLE 6.- EFFECT OF METHOD OF FABRICATION ON TENSILE AND CREEP PROPERTIES OF CERIUM-MANGANESE-MAGNESIUM ALLOYS - Continued

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A4976	2.23	1.90	0.31 Ni	Extrusion	HTA[k]	70	26,200	32,250	7.0	7.3	------	-----	-------	-----	-----	-----
					HTA	70	30,700	32,250	1.5	1.1	------	-----	-------	-----	-----	-----
					HTAS[k]	600	[l]8,700	[l]12,500	[l]32.5	[l]84.0	284.3	-----	0.0015	0.262	0.635	-----
					HTAS	600	9,375	12,700	84.2	67.5	287	0.041	.00025	.110	.167	0.043
				Sand-cast	HTAS	600	6,500	9,400	3.0-54.0	2.8-48.4	336	.039	.00025	.083	.182	.048
					HTAS	600	------	-------	---------	---------	312	.041	.00032	.095	.160	.044
A5600	2.05	1.75	.25 Ni	Extrusion	HTA	70	------	28,425	1.0	1.0	------	-----	-------	-----	-----	-----
					HTA	300	18,400	22,650	3.7	4.0	------	-----	-------	-----	-----	-----
					HTAS[m]	400	14,125	19,500	10.2	14.1	------	-----	-------	-----	-----	-----
					HTAS[n]	500	11,750	17,300	20.0	18.5	------	-----	-------	-----	-----	-----
					HTAS	600	8,200	11,500	51.5	39.2	[o]509	.026	.00012	.037	.077	.020
					HTAS	600	------	-------	---------	---------	[o]305	.028	.00012	.063	.088	.023
					HTAS	600	------	-------	---------	---------	[p]312	.049	.0009	.213	.403	.050
				Sand-cast	HTA	70	------	10,000	.8	.8	------	-----	-------	-----	-----	-----
					HTAS	600	6,750	10,100	17.0-60.0	20.6-43.8	232	.042	.00048	.125	.187	.023
				0.070-in. rolled sheet	HTA[q]	70	10,425	17,775	3.5	---------	------	-----	-------	-----	-----	-----
					HTAS	600	------	7,900	66.5	---------	------	-----	-------	-----	-----	-----
A5601	2.13	1.92	.27 Ni	Extrusion	HTA	70	27,000	29,250	1.7	1.4	------	-----	-------	-----	-----	-----
					HTA	300	16,700	22,375	9.2	9.0	------	-----	-------	-----	-----	-----
					HTAS[m]	400	11,000	16,250	18.0	23.7	------	-----	-------	-----	-----	-----
					HTAS[n]	500	10,200	14,950	27.0	41.2	------	-----	-------	-----	-----	-----
					HTAS	600	7,325	10,950	92.7	66.2	482	.042	.00022	.130	.242	.044
					HTAS	600	------	-------	---------	---------	[p]338	.055	.00088	.205	.393	.042
				Sand-cast	HTA	70	------	9,000	.8	.6	------	-----	-------	-----	-----	-----
					HTAS	600	6,425	9,450	5.0-45.0	3.9-48.2	233	.038	.00005	.058	.065	.033
A4977	[j]2.00	[j]1.70	[j].20 Ni, [j].02 W	Extrusion	HTA	70	28,850	30,000	[l]1.0	[l]1.1	------	-----	-------	-----	-----	-----
					HTAS	600	9,900	13,400	62.5	53.6	312	.049	.00030	.135	.200	.031
				Sand-cast	HTA	70	------	13,125	1.0	1.0	------	-----	-------	-----	-----	-----
					HTAS	600	6,850	10,350	62.0	59.0	------	-----	-------	-----	-----	-----

[a] HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS same as HTA and stabilized 24 hr at 650° F following the aging treatment.
HTQAS aged and stabilized as above except water-quenched from the solution-heat-treating temperature.
Ann. furnace-cooled from solution-heat-treating temperature.

[b] Each tensile property is the average of two test results unless otherwise specified.

[j] Intended composition.

[k] Solution-heat-treated at 1000° F.

[l] Value for one test bar.

[m] Stabilized 24 hr at 500° F.

[n] Stabilized 24 hr at 575° F.

[o] At 1300-psi stress.

[p] At 2500-psi stress.

[q] Damaged in heat treatment.

TABLE 6.- EFFECT OF METHOD OF FABRICATION ON TENSILE AND CREEP PROPERTIES OF CERIUM-MANGANESE-MAGNESIUM ALLOYS - Concluded

Heat	Analysis			Method of fabrication	Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)	Others (percent)				Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
A5464	[j]2.00	[j]1.70	0.20 Ni, 0.50 Zr, [j]0.01 Be	Extrusion	HTA	70	28,000	30,900	2.5	2.8	---	-----	------	-----	-----	-----
					HTAS	600	8,850	12,100	93.5	72.0	---	-----	------	-----	-----	-----
				0.080-in. rolled sheet	HTA	70	14,900	26,650	12.5	----	---	-----	------	-----	-----	-----
					HTAS	600	------	8,350	38.0-85.0	----	---	-----	------	-----	-----	-----
A4846	4.50	.62	----------	Extrusion	HTA	70	26,175	30,850	6.5	[l]9.2	---	-----	------	-----	-----	-----
					HTAS	600	6,150	10,400	126.0	92.7	47	0.043	0.0905	-----	3.88	0.040
					HTAS	600	------	-------	---------	----	143	.045	.030	4.67	5.64	.040
				$\frac{1}{4}$- in. rolled plate	HTA	70	18,400	27,000	6.1	----	---	-----	------	-----	-----	-----
A4845	4.50	1.03	----------	Extrusion	HTA	70	25,250	30,700	5.5	----	---	-----	------	-----	-----	-----
					HTAS	600	6,575	10,675	125.0	90.3	93	.041	.0595	-----	5.04	.040
					HTAS	600	------	-------	---------	----	142	.038	.0230	4.43	5.65	.050
				$\frac{1}{4}$- in. rolled plate	HTA	70	18,150	26,950	5.7	----	---	-----	------	-----	-----	-----
A4844	4.39	1.38	----------	Extrusion	HTA	70	24,850	30,250	3.5	4.9	---	-----	------	-----	-----	-----
					HTAS	600	6,700	10,800	129.0	86.1	149	.045	.0195	2.85	3.18	.040
					HTAS	600	------	------	-----	----	143	.043	.0160	5.00	6.08	.050
				$\frac{1}{4}$- in. rolled plate	HTA	70	20,500	27,200	4.1	----	---	-----	------	-----	-----	-----
A4848	6.27	1.60	----------	Extrusion	HTA	70	31,400	33,100	3.5	3.9	---	-----	------	-----	-----	-----
					HTAS	600	7,400	12,150	121.0	85.5	114	.041	.0520	-----	4.92	.050
					HTAS	600	------	-------	---------	----	194	.043	.014	1.76	2.68	.040
				Sand-cast	HTA	70	[l]6,530	11,075	35.0	37.0	---	-----	------	-----	-----	-----
A4850	[j]6.00	[j]1.70	[j]0.50 Al	Extrusion	HTA	70	27,550	29,875	4.0	1.9	---	-----	------	-----	-----	-----
					HTAS	600	6,400	11,600	97.5	80.8	145	.047	.0023	.340	.412	.040
				Sand-cast	HTA	70	[l]5,500	[l]11,000	[l]27.0	[l]26.1	---	-----	------	-----	-----	-----
				$\frac{1}{4}$- in. rolled plate	HTA	70	18,825	23,750	3.3	-----	---	-----	------	-----	-----	-----

[a] HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS same as HTA and stabilized 24 hr at 650° F following the aging treatment.
HTQAS aged and stabilized as above except water-quenched from the solution-heat-treating temperature.
Ann. furnace-cooled from solution-heat-treating temperature.

[b] Each tensile property is the average of two test results unless otherwise specified.

[j] Intended composition.

[l] Value for one test bar.

TABLE 7.- EFFECT OF VARIOUS HEAT TREATMENTS ON PROPERTIES OF SAND-CAST, EXTRUDED, AND ROLLED EM42 ALLOY

Heat	Analysis		Heat treatment (a)	Test temperature (°F)	Tensile properties (b)				Creep properties at a 2000-psi stress					
	Ce (percent)	Mn (percent)			Yield strength, 0.2-percent offset (psi)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Duration (hr)	Initial deformation (percent)	Minimum creep rate (percent/hr)	Deformation at end of 120 hr (percent)	Total deformation (percent)	Contraction on release of load (percent)
Sand-cast														
A4932	4.25	1.51	Aged	70	------	13,850	-----	0.8	-----	-----	-------	-----	-----	-----
A4931	4.45	1.50	Aged	600	8,175	12,900	19.2	25.1	304.0	0.041	0.00035	0.099	0.158	0.037
A4932	4.25	1.51	A&S	70	------	13,850	[c].8	[c].4	-----	-----	-------	-----	-----	-----
A4930	4.44	1.50	A&S	600	7,050	10,300	33.0	35.1	286.0	.047	.00027	.105	.185	.053
A4929	4.40	1.49	HTA	70	------	16,300	1.0	[c].8	-----	-----	-------	-----	-----	-----
A4931	4.45	1.50	HTAS	600	6,700	9,575	38.5	52.8	311.0	.040	.00008	.075	.082	.042
A4929	4.40	1.49	HTQA	70	------	16,350	1.0	1.3	-----	-----	-------	-----	-----	-----
A4928	4.43	1.48	HTQAS	600	6,600	9,700	31.7	45.5	311.0	.045	.00022	.090	.140	.035
A5111	4.03	1.61	HTA	70	------	16,450	1.0	.4	-----	-----	-------	-----	-----	-----
			HTQAS	600	6,625	9,925	30.0	38.2	-----	-----	-------	-----	-----	-----
A4929	4.40	1.49	HTQA[d]	70	------	17,250	1.0	1.4	-----	-----	-------	-----	-----	-----
A4928	4.43	1.48	HTQAS[d]	600	6,100	9,275	22.5	37.6	314.0	.044	.00015	.085	.181	.039
3/4-inch extrusion														
A4932	4.25	1.51	Aged	70	33,000	38,000	4.0	3.3	-----	-----	-------	-----	-----	-----
A4932			Aged	600	7,400	10,400	108.5	91.0	-----	-----	-------	-----	-----	-----
A4931	4.45	1.50	Aged	600	------	------	-----	----	306.0	0.039	0.0045	0.630	1.37	0.010
A4932	4.25	1.51	A&S	70	29,850	35,550	5.5	5.8	-----	-----	-------	-----	-----	-----
A4930	4.44	1.50	A&S	600	7,800	10,450	133.7	92.7	-----	-----	-------	-----	-----	-----
A4931	4.45	1.50	A&S	600	------	------	-----	----	98.0	.042	.019	-----	1.77	.050
A4929	4.40	1.49	HTA	70	34,300	37,150	4.1	6.2	-----	-----	-------	-----	-----	-----
A4928	4.43	1.48	HTAS	600	7,550	11,275	106.3	86.5	170.0	.042	.0038	.495	.682	.046
A4931	4.45	1.50	HTAS	600	------	------	-----	----	306.0	.042	.00025	.197	.312	.036
A4931	4.45	1.50	HTAS	600	------	------	-----	----	306.0	.044	.0014	.275	.670	.042
A5111	4.03	1.61	HTA	70	32,400	37,900	3.5	3.0	-----	-----	-------	-----	-----	-----
			HTQAS	600	7,825	11,700	83.7	73.3	-----	-----	-------	-----	-----	-----
A4929	4.40	1.49	HTQA	70	38,125	41,000	3.5	4.1	-----	-----	-------	-----	-----	-----
A4928	4.43	1.48	HTQAS	600	7,875	11,400	115.0	91.5	305.0	.034	.0007	.268	.406	.030
A4928	4.43	1.48	HTQA[d]	70	33,325	38,500	5.0	4.8	-----	-----	-------	-----	-----	-----
			HTQAS[d]	600	7,800	11,100	146.2	94.7	331.0	.047	.00045	.215	.317	.043
0.060-inch rolled sheet														
A4895	3.95	1.40	Aged	70	------	36,200	[c]3.5	----	-----	-----	-------	-----	-----	-----
			Aged	600	------	8,050	39.5	----	18.0	0.057	(e)	-----	-----	-----
A4895	3.95	1.40	A&S	70	------	32,000	11.5	----	-----	-----	-------	-----	-----	-----
			A&S	600	------	6,450	18.0	----	-----	-----	-------	-----	-----	-----
A4895	3.95	1.40	HTA	70	------	31,000	7.0	----	-----	-----	-------	-----	-----	-----
			HTAS	600	[c]6,850	[c]8,400	[c]10.0	----	163.0	.048	0.010	2.52	2.93	0.04
			HTAS	600	------	------	-----	----	119.0	.022	.040	4.90	4.90	.04

[a] Aged heated 16 hr at 400° F and air-cooled.
A&S stabilized 24 hr at 650° F after above aging treatment.
HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS solution-heat-treated 24 hr at 1040° F, air-cooled, aged 16 hr at 400° F, and stabilized 24 hr at 650° F.
HTQA solution-heat-treated 24 hr at 1040° F, quenched in water, and aged 16 hr at 400° F.
HTQAS same as HTQA and stabilized 24 hr at 650° F following the aging treatment.
[b] Each tensile property is the average of two test results unless otherwise specified.
[c] One test value.
[d] Oil-quenched.
[e] Creep rate very high.

TABLE 8.- SPECIMENS EXAMINED BY MICROSCOPE, X-RAY DIFFRACTION, OR ELECTRON-MICROSCOPE METHOD

Specimen	Method of fabrication	Analysis			Heat treatment (a)	Minimum creep rate at stress of 2000 psi (percent/hr)	Deformation at end of 120 hr (percent)	Method of examination (b)	Remarks
		Ce (percent)	Mn (percent)	Others (percent)					
A4843-X5	Extruded	4.34	1.66	-------	HTAS	0.0425	4.000	M	
A4849-X5	Extruded	2.47	1.68	-------	HTAS	.0057	.800	XD, EM	This specimen had a high creep rate as compared with specimen A4975-X5
A4928-A1	Cast	4.43	1.48	-------	HTQA	-------	-----	M	
A4928-B1	Cast	4.43	1.48	-------	HTQA[c]	-------	-----	M	
A4928-X1	Extruded	4.43	1.48	-------	HTA	-------	-----	M	
A4928-X4	Extruded	4.43	1.48	-------	HTAS	.0038	.495	M	
A4928-X8	Extruded	4.43	1.48	-------	HTQAS	.0007	.268	M	
A4928-X12	Extruded	4.43	1.48	-------	HTQAS[c]	.00045	.215	M	
A4930-A1	Cast	4.44	1.50	-------	HTA	-------	-----	M	
A4930-B4	Cast	4.44	1.50	-------	A&S	.00027	.105	M	
A4931-B4	Cast	4.44	1.50	-------	Aged	.00035	.099	M	
A4931-A4	Cast	4.44	1.50	-------	HTAS	.00008	.075	M	
A4931-X1	Extruded	4.44	1.50	-------	HTAS	.00025	.197	M, XD	These specimens from the same heat showed a marked difference in creep properties
A4931-X7	Extruded	4.44	1.50	-------	HTAS	.0014	.275	M, XD	
A4970-X2	Extruded	2.24	1.24	-------	HTA	-------	-----	M	
A4971-X2	Extruded	[d]2.00	1.24	-------	HTA	-------	-----	M	
A4972-X2	Extruded	2.45	1.55	-------	HTA	-------	-----	M	
A4973-X2	Extruded	6.01	1.81	-------	HTA	-------	-----	M	
A4973-X5	Extruded	6.01	1.81	-------	HTAS	.0020	.504	M	
A4973-X6	Extruded	6.01	1.81	-------	HTQAS	.00043	.230	M	
A4973-X8	Extruded	6.01	1.81	-------	Ann.	.077	9.000	M	
A4974-X2	Extruded	4.31	1.77	-------	HTA	-------	-----	M	
A4974-X5	Extruded	4.31	1.77	-------	HTAS	.0034	.520	M, XD	These specimens differed in creep properties as a result of the difference in heat treatment
A4974-X6	Extruded	4.31	1.77	-------	HTQAS	.0006	.300	M, XD	
A4974-X8	Extruded	4.31	1.77	-------	Ann.	.060	-----	M	
A4975-A1	Cast	2.41	1.90	-------	HTAS	.00015	.080	M, XD, EM	Examined to compare structure with A4975-X5
A4975-B1	Cast	2.41	1.90	-------	HTAS	.00030	.122	M	
A4975-X2	Extruded	2.41	1.90	-------	HTA			M	
A4975-X5	Extruded	2.41	1.90	-------	HTAS	.0008	.294	M, XD, EM	Examined (1) to show effect of heat treatment on a structure and (2) to compare method of fabrication
A4975-X6	Extruded	2.41	1.90	-------	HTQAS	.0035	.500	M, XD, EM	
A4975-X8	Extruded	2.41	1.90	-------	Ann.	.175	-----	M, XD, EM	

[a]Aged heated 16 hr at 400° F and air-cooled.
A&S stabilized 24 hr at 650° F after above aging treatment.
HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS solution-heat-treated 24 hr at 1040° F, air-cooled, aged 16 hr at 400° F, and stabilized 24 hr at 650° F.
HTQA solution-heat-treated 24 hr at 1040° F, quenched in water, and aged 16 hr at 400° F.
HTQAS same as HTQA and stabilized 24 hr at 650° F following the aging treatment.
Ann. furnace-cooled from solution-heat-treating temperature.

[b]M, microscope; XD, X-ray diffraction; EM, electron microscope.

[c]Oil-quenched.

[d]Intended composition.

TABLE 8.- SPECIMENS EXAMINED BY MICROSCOPE, X-RAY DIFFRACTION, OR ELECTRON-MICROSCOPE METHOD - Concluded

Specimen	Method of fabrication	Analysis			Heat treatment (a)	Minimum creep rate at stress of 2000 psi (percent/hr)	Deformation at end of 120 hr (percent)	Method of examination (b)	Remarks
		Ce (percent)	Mn (percent)	Others (percent)					
A4975-LB	Rolled sheet	2.41	1.90	----------	HTAS	0.0055	0.750	M	
A4975-TB	Rolled sheet	2.41	1.90	----------	HTAS	.0065	.812	M	
A4976-X2	Extruded	2.23	1.90	0.31 Ni	HTA			M	
A4976-X5	Extruded	2.23	1.90	.31 Ni	HTAS	.00025	.110	M, XD	Examined to determine the effects of nickel
A4976-X7	Extruded	2.23	1.90	.31 Ni	HTAS[e]	.0015	.635	M	
A4977-X2	Extruded	[d]2.00	[d]1.70	[d].20 Ni, [d].02 W	HTA	-------	-----	M	
A4978-X2	Extruded	2.15	1.90	[d].20 Ni, [d].50 Cd	HTA	-------	-----	M	
A4979-X2	Extruded	[d]2.00	[d]1.70	[d].50 Cd, [d].20 Ni, [d].02 W	HTA	-------	-----	M	
A4980-X2	Extruded	[d]2.00	[d]1.70	[d].50 Cd	HTA	-------	-----	M	
A4981-X2	Extruded	.75	1.56	----------	HTA	-------	-----	M	
A4993-X2	Extruded	.0	1.80	----------	HTA	-------	-----	M	
A4993-X5	Extruded	.0	1.80	----------	HTAS	.0046	.680	M	
A4993-X6	Extruded	.0	1.80	----------	HTQAS	.0003	.090	M	
A5107-X5	Extruded	2.33	0	----------	HTAS	.170	-----	M, XD, EM	Used as basis for comparison for magnesium-manganese-cerium alloys
A5107-X7	Extruded	2.33	0	----------	HTQAS	.106	-----	M	
A5109-X5	Extruded	.41	1.65	----------	HTAS	.0020	.301	M	
A5109-X7	Extruded	.41	1.65	----------	HTQAS	.0040	2.92	M	
A5109-X9	Extruded	.41	1.65	----------	Ann.	.077	-----	M	
A5110-X5	Extruded	1.34	1.56	----------	HTAS	.0014	.303	M	
A5110-X7	Extruded	1.34	1.56	----------	HTQAS	.001	.375	M	
A5110-X9	Extruded	1.34	1.56	----------	Ann.	.057	7.50	M	
A5257-X5	Extruded	0	1.84	----------	HTAS	.012	-----	XD	To determine the effect of water-quenching from solution-heat-treating temperature on structure
A5257-X9	Extruded	0	1.84	----------	HTQAS	.00046	.114	XD	
A5454-X5	Extruded	[d]2.00	[d]1.70	[d].20 Ni	HTAS	.0002	.088	M	
A5459-X5	Extruded	2.09	1.72	.24 Ni, .14 Al	HTAS	.0009	.255	M	
A5465-X5	Extruded	[d]2.00	[d]1.70	[d].20 Ni	HTAS	.0002	.132	M	
A5600-X4	Extruded	2.05	1.75	.25 Ni	HTAS	-------	-----	M	
A5601-X5	Extruded	2.13	1.92	.27 Ni	HTAS	.00022	.130	M	

[a]Aged heated 16 hr at 400° F and air-cooled.
A&S stabilized 24 hr at 650° F after above aging treatment.
HTA solution-heat-treated 24 hr at 1040° F, air-cooled, and aged 16 hr at 400° F.
HTAS solution-heat-treated 24 hr at 1040° F, air-cooled, aged 16 hr at 400° F, and stabilized 24 hr at 650° F.
HTQA solution-heat-treated 24 hr at 1040° F, quenched in water, and aged 16 hr at 400° F.
HTQAS same as HTQA and stabilized 24 hr at 650° F following the aging treatment.
Ann. furnace-cooled from solution-heat-treating temperature.
[b]M, microscope; XD, X-ray diffraction, EM, electron microscope.
[d]Intended composition.
[e]Solution-heat-treated at 1000° F.

TABLE 9.- X-RAY DIFFRACTION RESULTS ON SEVERAL EXTRUDED AND ONE CAST ALLOY

X-ray	Specimen	Analysis			Description (1)	Minimum creep rate at 600° F (percent/hr)	Intensities of phase patterns observed (2)								Remarks
		Ce (percent)	Mn (percent)	Ni (percent)			Mg, I	X		Y[3]		Mn		Others	
								I	Br	I	BR	I	BR		
5A	A5257-X5	-----	1.84	----	HTAS, as filed	0.012	VS	0	----	0	---	F[4]	sh?	----------	Average of two films
5E	A5257-X5	-----	1.84	----	Extraction in NH_4Cl, 4N	.012	O	0	----	0	---	MS[4]	sh	F unknown	----------
6A	A5257-X9	-----	1.84	----	HTQAS, as filed	.00046	S	0	----	0	---	F[4]	sl.d	----------	Average of three films, ferrite and austenite in one
8A	A4849-X5	2.47	1.68	----	HTAS, as filed	.0057	VS	VF	d?	VVF	d?	F[4]	sh?	Unknown ?	Average of two films
7A1	A4975-A1	2.41	1.90	----	Cast, as filed, X-section	.00015	VS	VVF?	?	O?	---	VF	sh?	----------	Average of two films
7A3	A4975-A1	2.41	1.90	----	Cast-HTAS, as filed, center	.00015	VS	MF	sh	VVF	?	F	d	----------	----------
7B	A4975-A1	2.41	1.90	----	Extraction by Grignard	.00015	O	F	d	VVF?	---	M[4]	sh	X may be CeO_2	----------
7C	A4975-A1	2.41	1.90	----	Extraction in NH_4Cl, 2N	.00015	O	M	sh	O	---	F[4]	sh	X may be CeO_2	----------
9A	A4975-X5	2.41	1.90	----	HTAS, as filed	.0008	VS	F	d	tr?	d	F	d	poss. α Mn	Average of two films, ferrite and austenite in one
10A	A4975-X6	2.41	1.90	----	HTQAS, as filed	.0035	S	F	d	VVF	d?	VF	d	poss. α Mn	Average of two films
11A	A4975-X8	2.41	1.90	----	Ann., as filed	.175	S	tr	?	VVF	sh	VF[4]	sh?	----------	Average of two films
12A	A4931-X1	4.45	1.50	----	HTAS, as filed	.00025	S	F	sh	VVF	sh?	F[4]	sl.d	poss. α Mn	Average of two films
13A	A4931-X7	4.45	1.50	----	HTAS, as filed	.0014	VS	F	d?	VF	sh?	F	d	poss. α Mn	Average of two films
15A	A4974-X5	4.31	1.77	----	HTAS, as filed	.0034	S	F	sh	VVF	sh	F	d	----------	Average of two films, ferrite in both
16A	A4974-X6	4.31	1.77	----	HTQAS, as filed	.0006	S	F	sl.d	VF	sh?	F	d	poss. α Mn	Average of two films, ferrite in one
16B	A4974-X6	4.31	1.77	----	Outside corrosion scale	-------	MF	O	----	O	---	O	----	MgO, CeO_2	----------
14A	A4976-X5	2.23	1.90	0.31	HTAS, as filed	.00025	S	F	d?	VVF	?	VF	sh	poss. α Mn	----------
18A	A5107	2.33	----	----	Heat-treated, as filed	-------	MS	O	----	VF	sh	O	----	----------	----------
19A	--------	35	----	----		-------	F	O	----	S	---	O	----	----------	----------

[1] HTAS solution-heat-treated 24 hr at 1040° F, air-cooled, aged 16 hr at 400° F, and stabilized 24 hr at 650° F.
HTQAS solution-heat-treated 24 hr at 1040° F, quenched in water, aged 16 hr at 400° F, and stabilized 24 hr at 650° F.
Ann. furnace-cooled from solution-heat-treating temperature.

[2] I intensity; M medium; tr trace; sl slightly; ? uncertain
Br breadth; F faint; sh sharp; poss possibly
S strong; V very; d diffuse; O none

[3] Y-phase has been tentatively identified as Mg_9Ce.

[4] Beta manganese definitely identified.

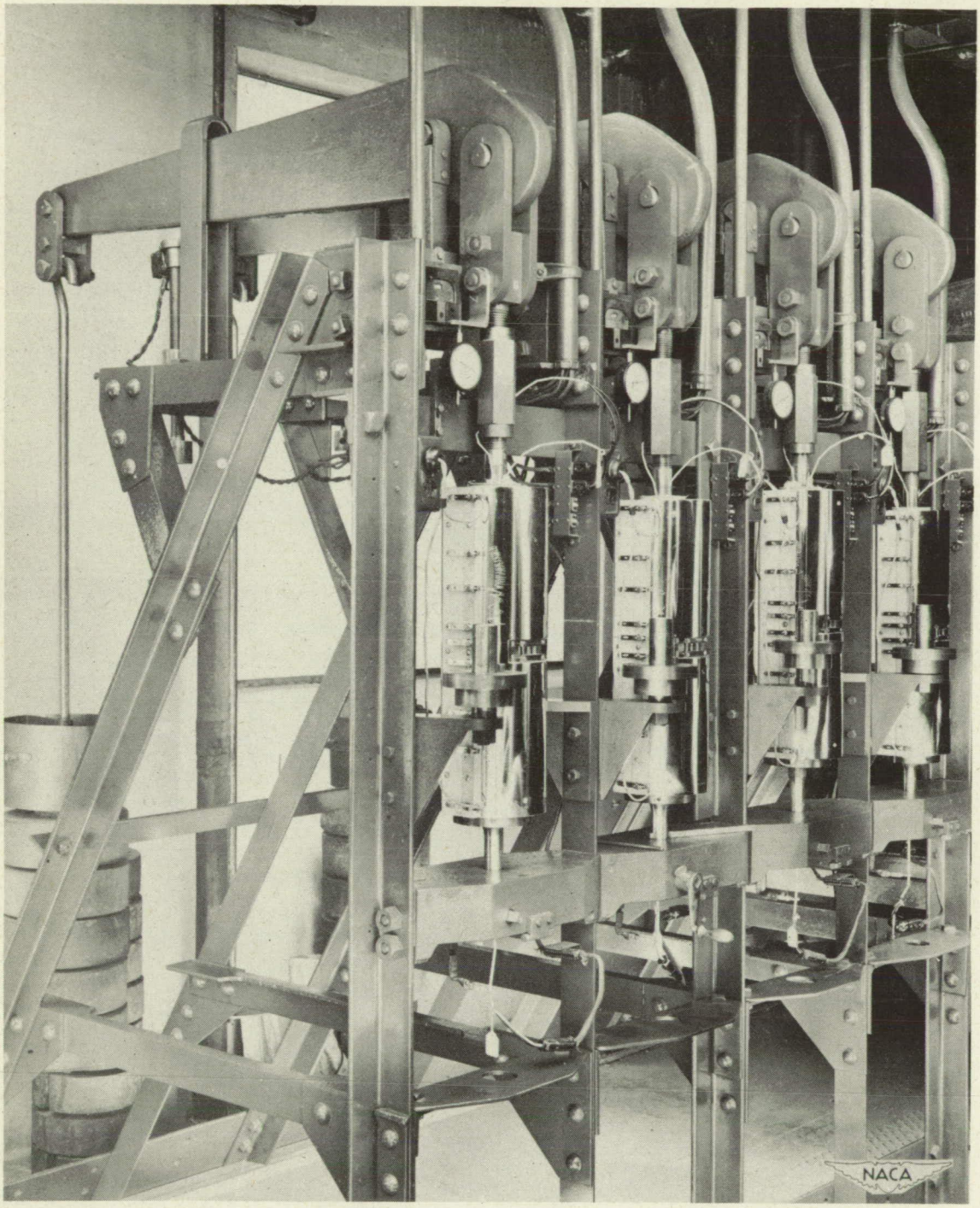


Figure 1.- Battelle creep or stress-rupture units.

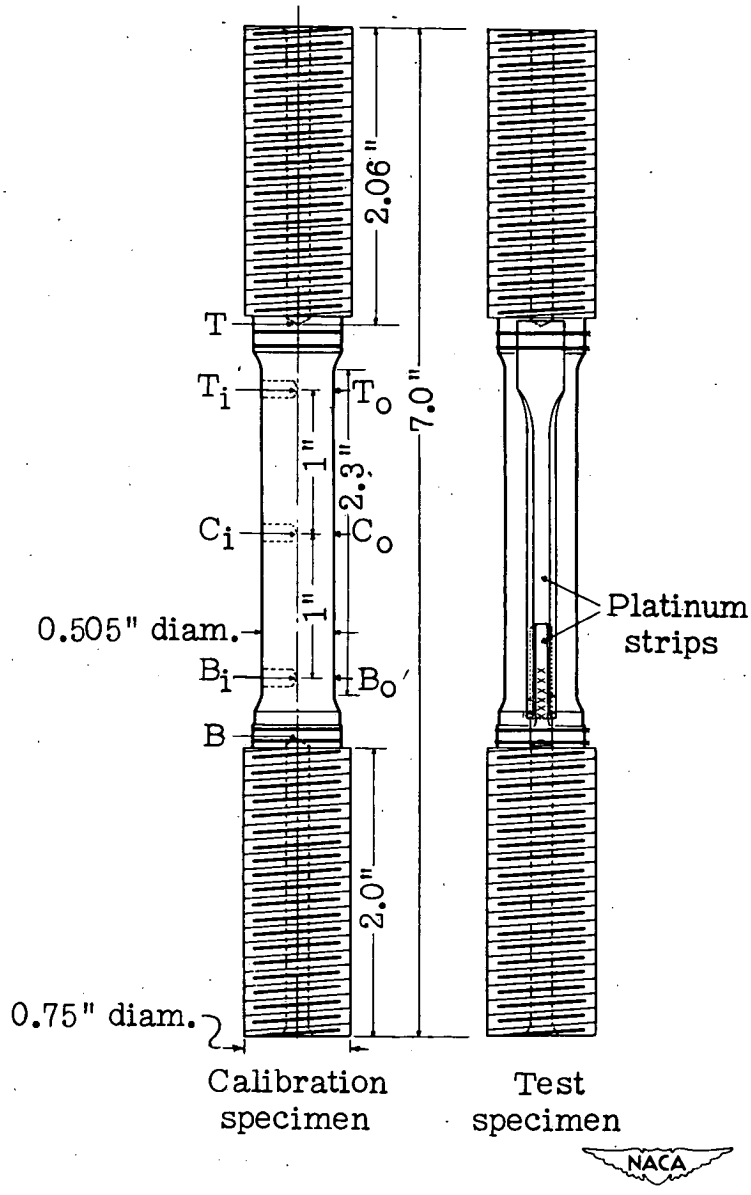


Figure 2.- Calibration and creep test specimens.

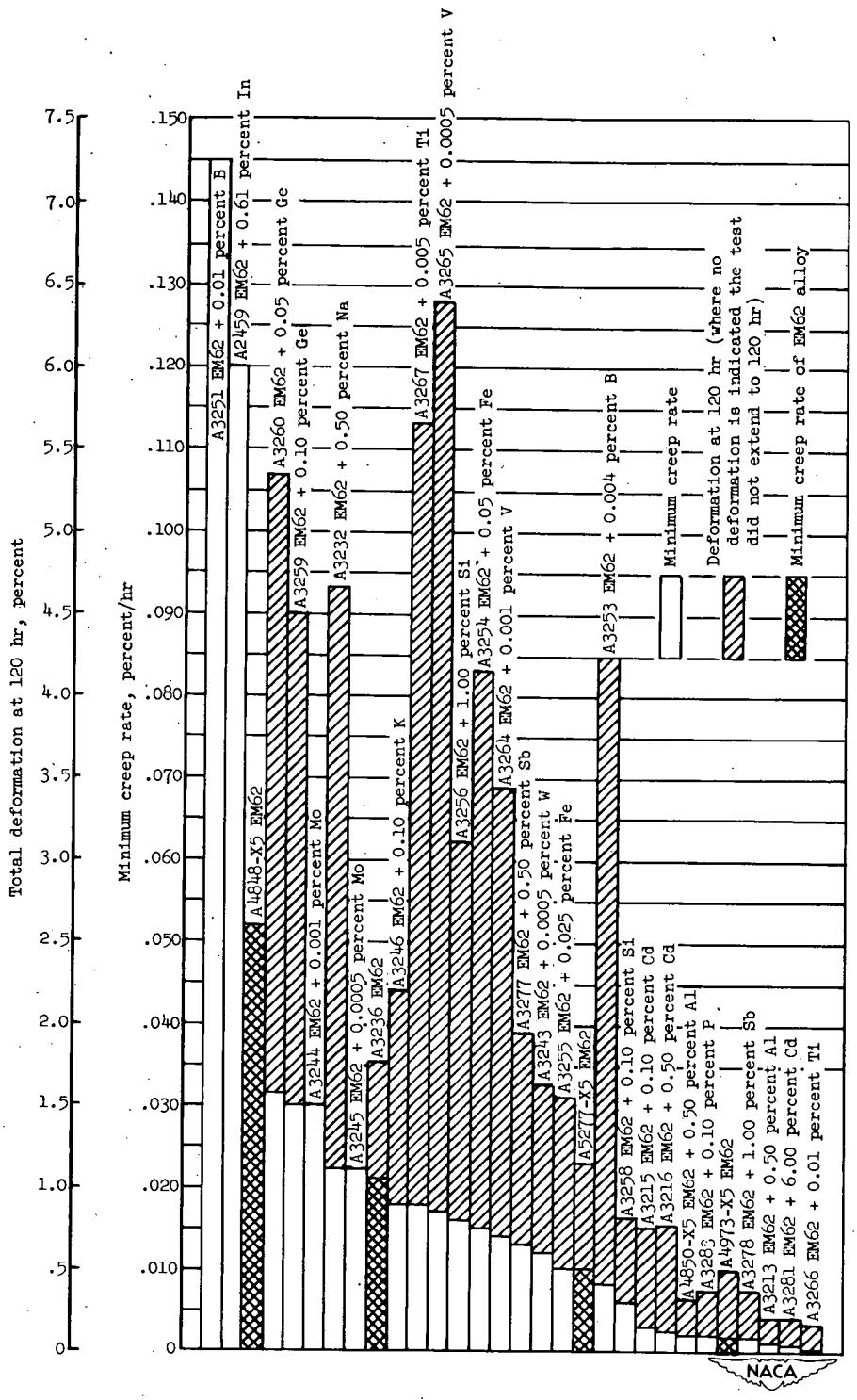


Figure 3.- Effects of small alloy additions on total deformation and minimum creep rate of extruded magnesium alloys containing 6 percent cerium and 1.7 percent manganese. Tested at 600° F under a 2000-psi stress. (Note scatter in values for EM62 composition.)

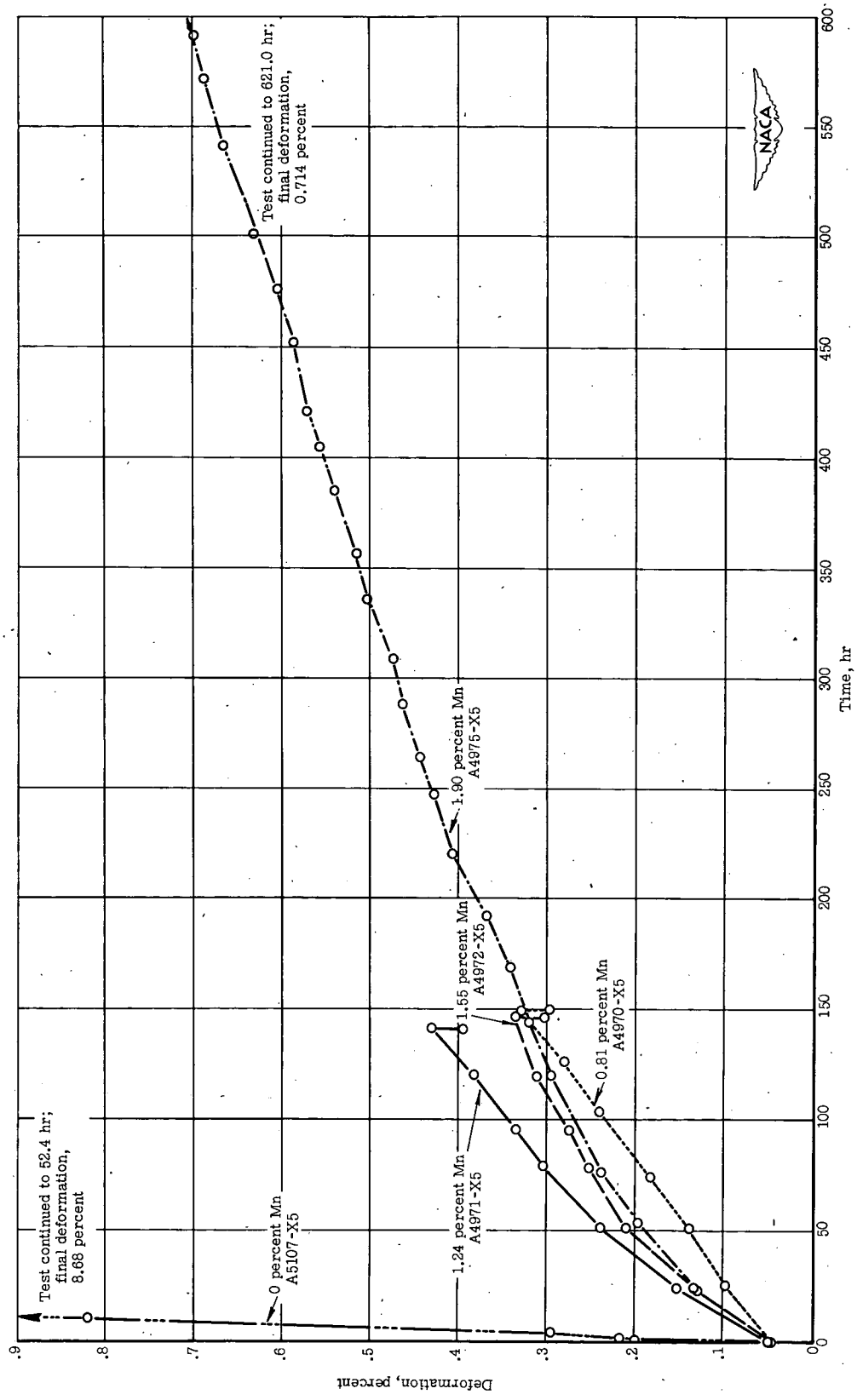


Figure 4.- Time-deformation curves showing effect of manganese content in an extruded magnesium-base alloy containing 2 percent cerium. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 2000-psi stress.

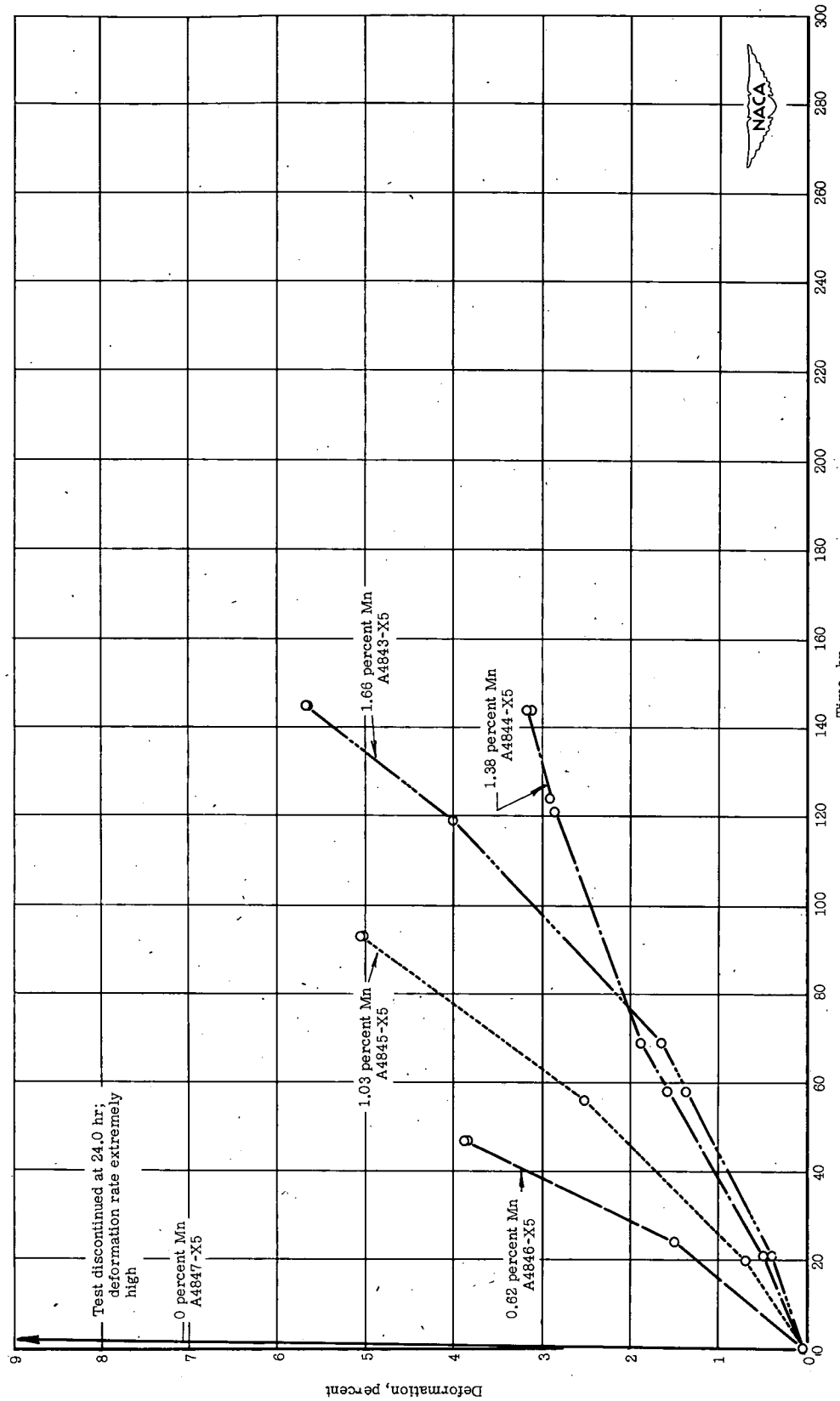


Figure 5.- Time-deformation curves showing effect of manganese content in an extruded magnesium-base alloy containing 4.0 to 4.5 percent cerium. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 2000-psi stress.

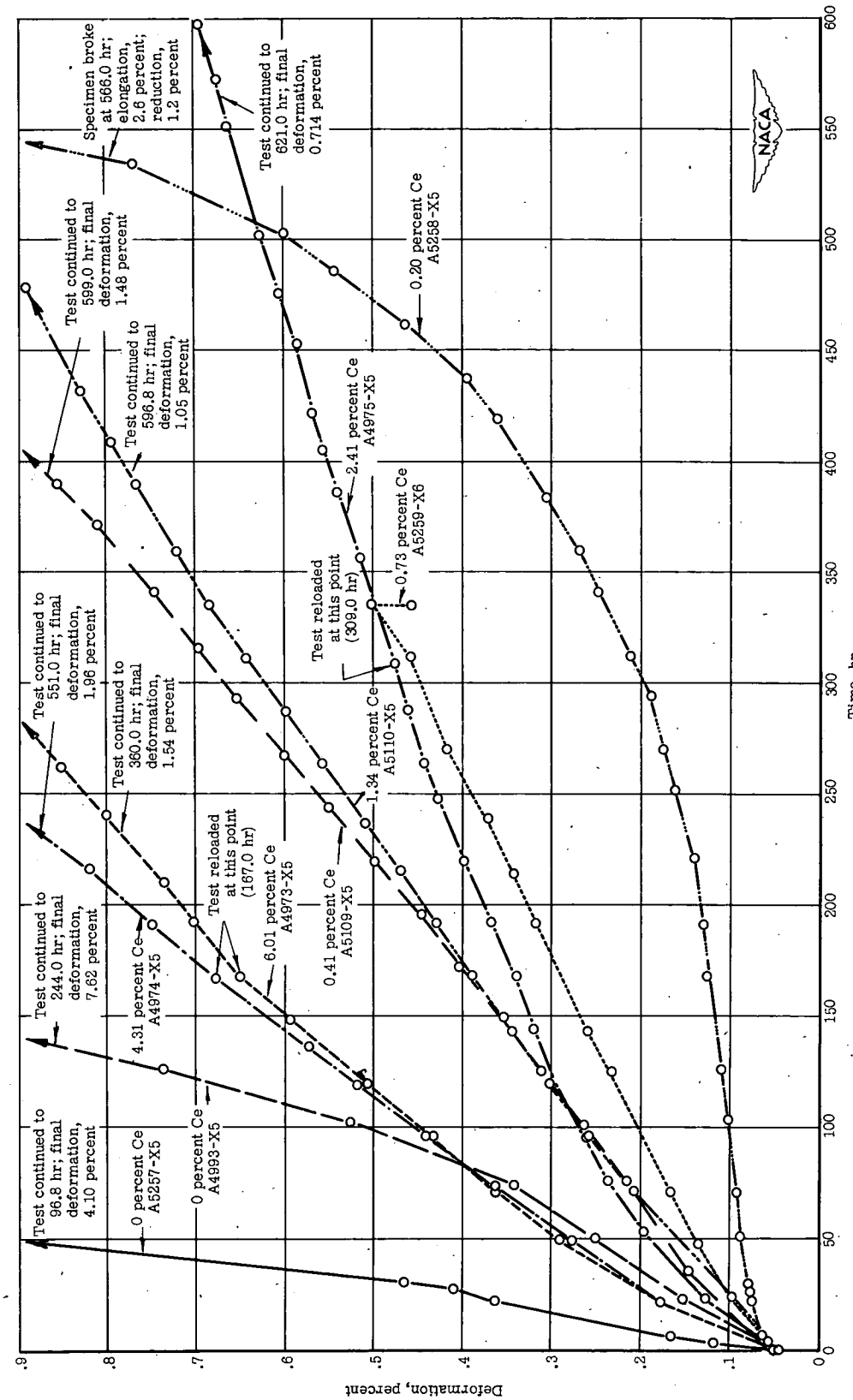


Figure 6.- Time-deformation curves showing effect of cerium content in extruded magnesium-base alloys containing 1.8 percent manganese. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 2000-psi stress.

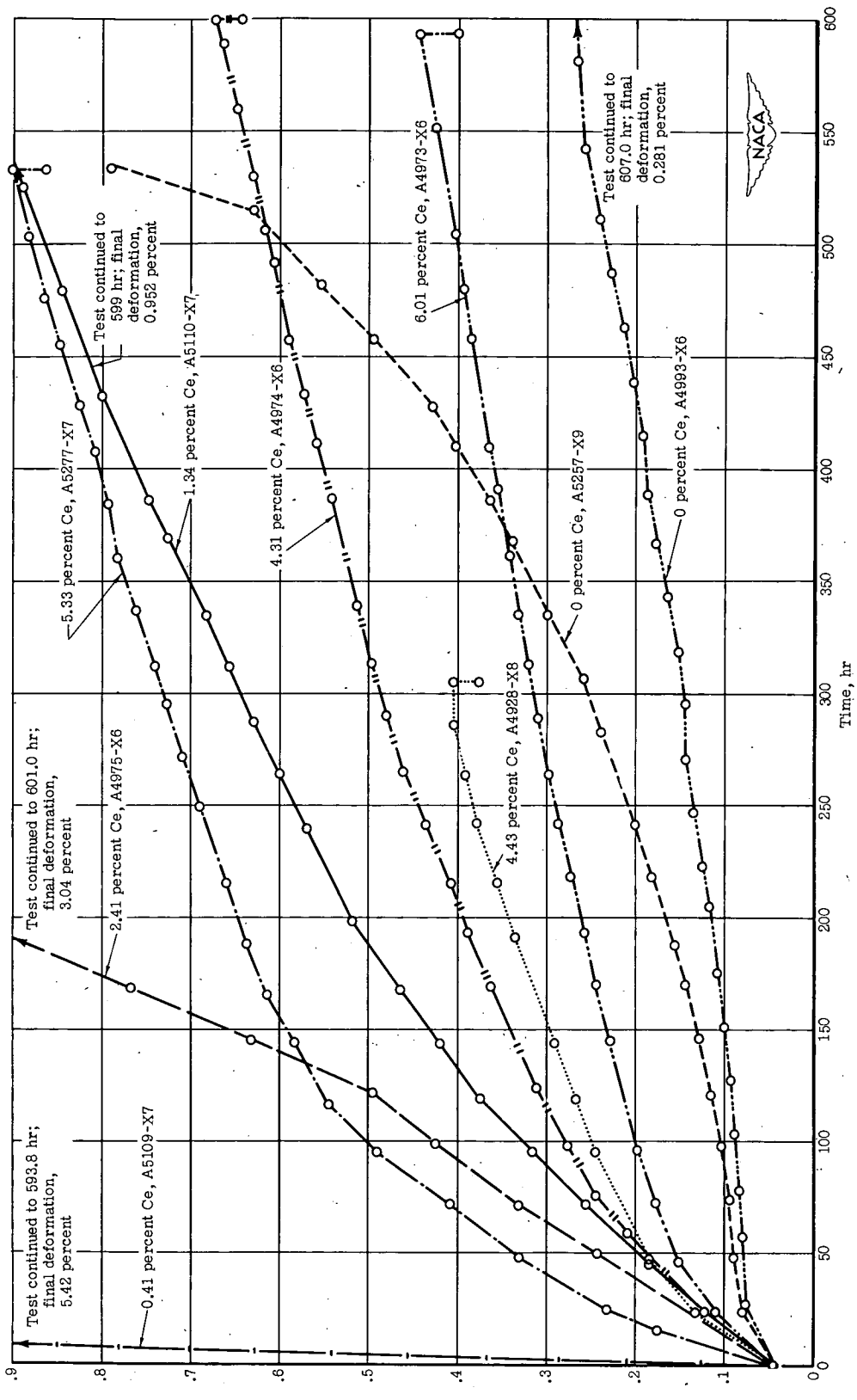


Figure 7.- Time-deformation curves showing effect of cerium content in extruded magnesium-base alloys containing 1.8 percent manganese. Specimens tested in heat-treated, quenched, aged, and stabilized condition at 600° F under a 2000-psi stress.

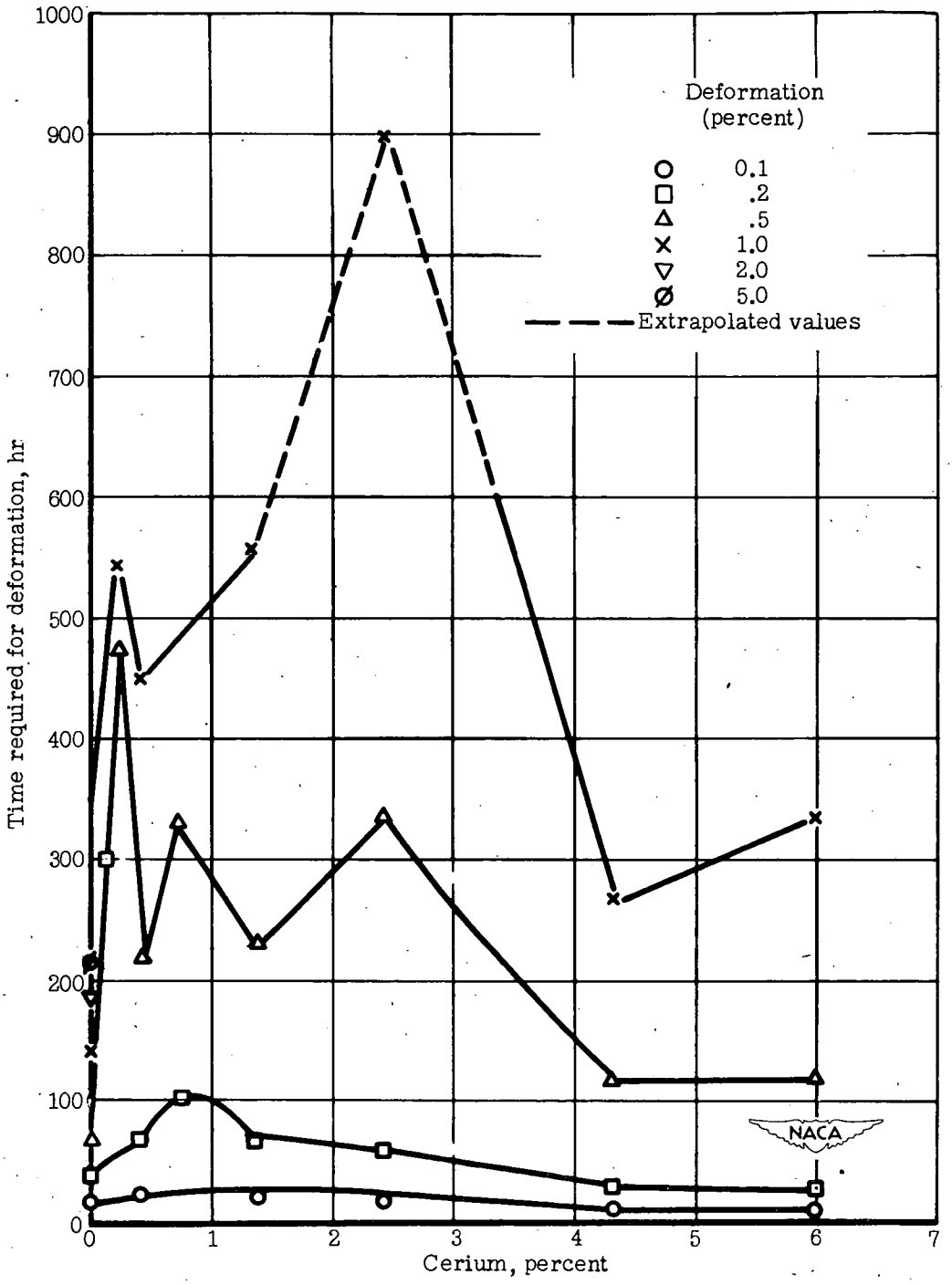


Figure 8.- Effect of cerium on time required to produce 0.1-, 0.2-, 0.5-, 1.0-, 2.0-, and 5.0-percent deformation in an extruded magnesium-base alloy containing 1.6 to 1.9 percent manganese. Specimens tested in heat-treated, aged, and stabilized condition for 244 to 621 hours at 600° F under a 2000-psi stress.

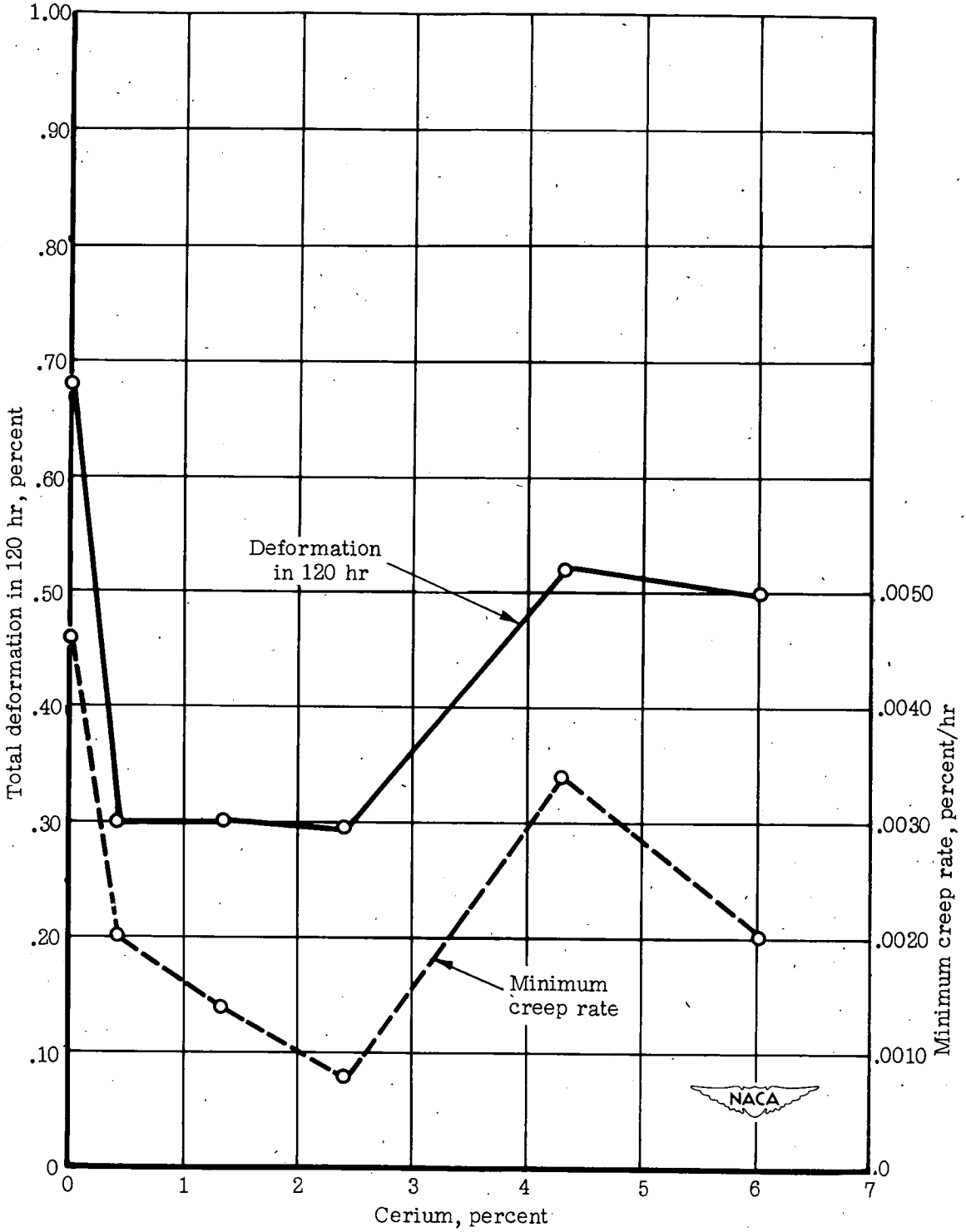


Figure 9.- Effect of cerium on minimum creep rate and total deformation at 120 hours in an extruded magnesium-base alloy containing 1.6 to 1.9 percent manganese. Specimens tested in heat-treated, aged, and stabilized condition for 244 to 621 hours at 600° F under a 2000-psi stress.

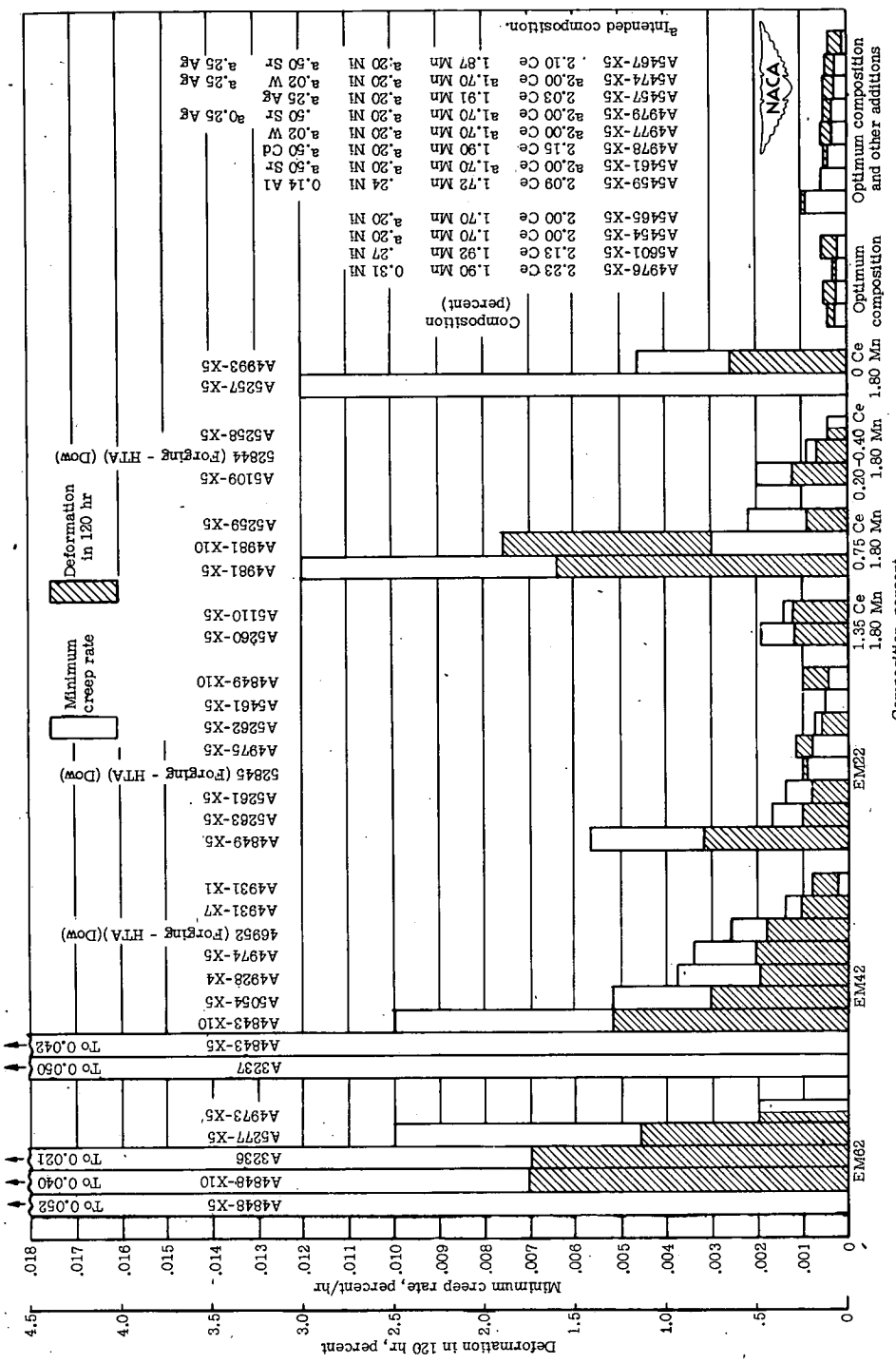


Figure 10.- Comparison of deformation in 120 hours and short-time minimum creep rates of magnesium alloys containing about 1.7 percent manganese and various amounts of cerium with or without other additions. Specimens tested in heat-treated, aged, and stabilized condition, except where noted, at 600° F under a 2000-psi stress.

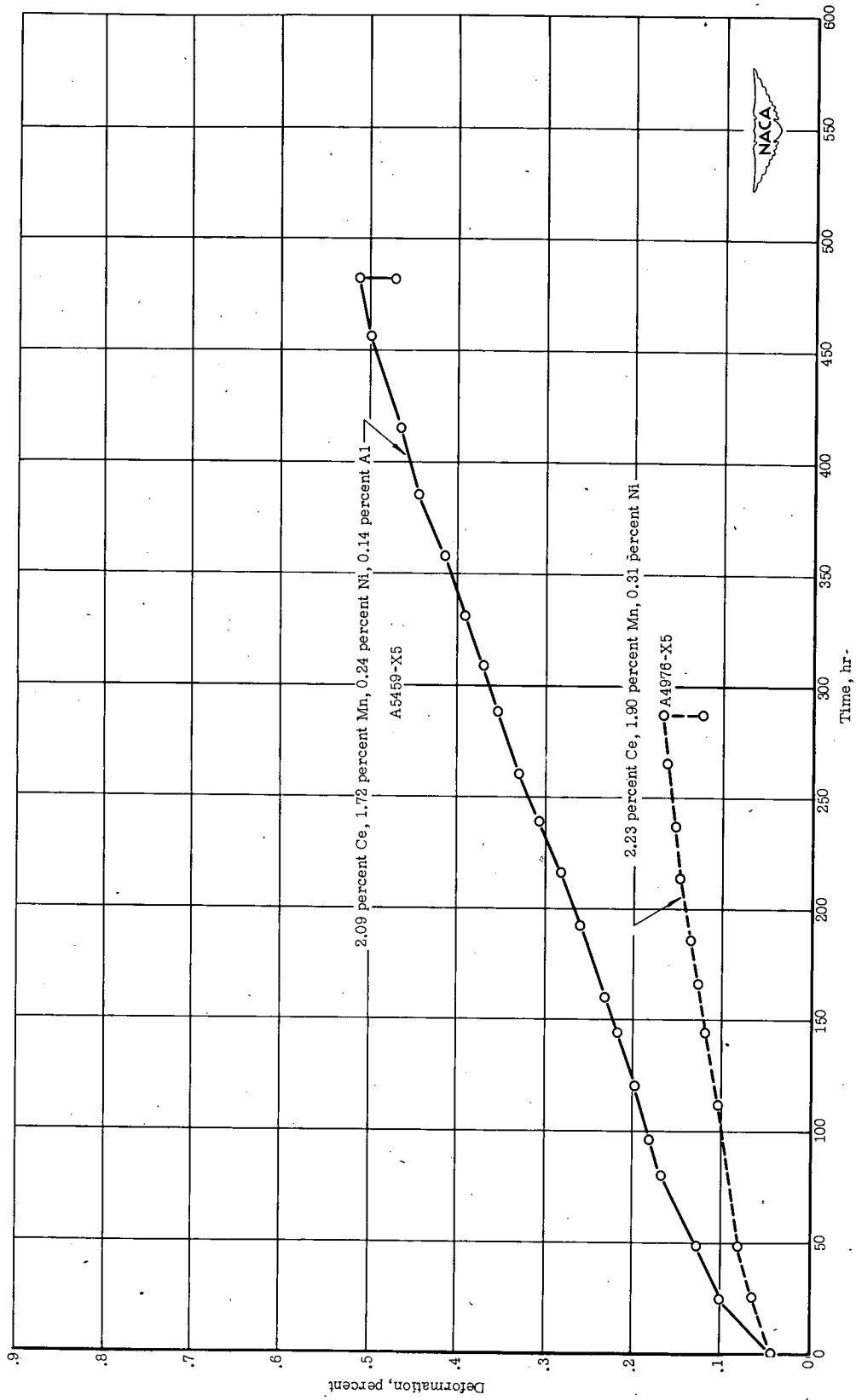


Figure 11.- Time-deformation curves showing effect of aluminum content in an extruded magnesium-base alloy containing cerium, manganese, and nickel. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 2000-psi stress.

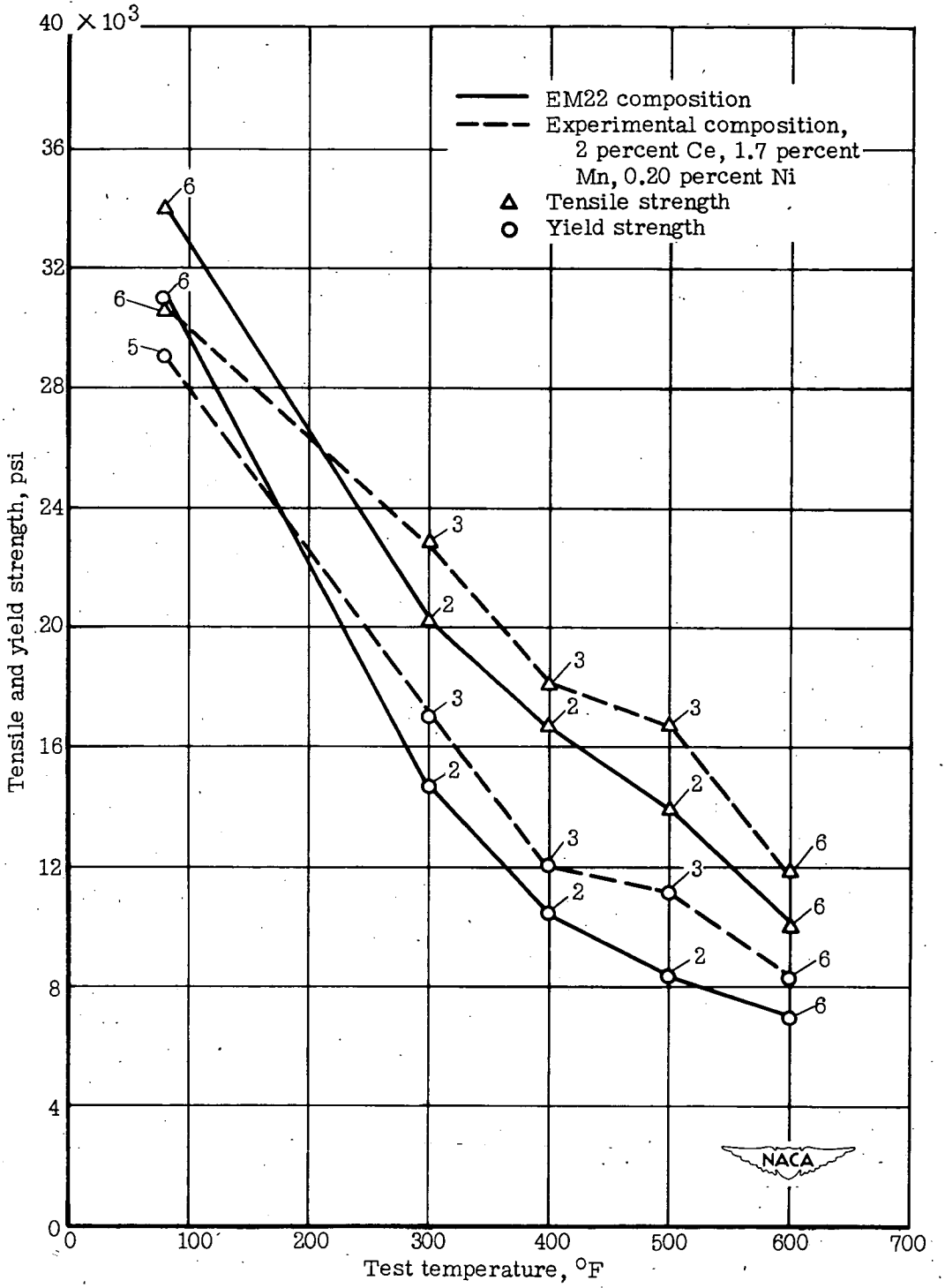


Figure 12.- Effect of temperature on tensile properties of extruded EM22 alloy and experimental alloy containing nickel. Specimens tested in heat-treated and aged condition at room temperature and in heat-treated, aged, and stabilized condition at elevated temperatures. Numbers by test points indicate number of heats tested.

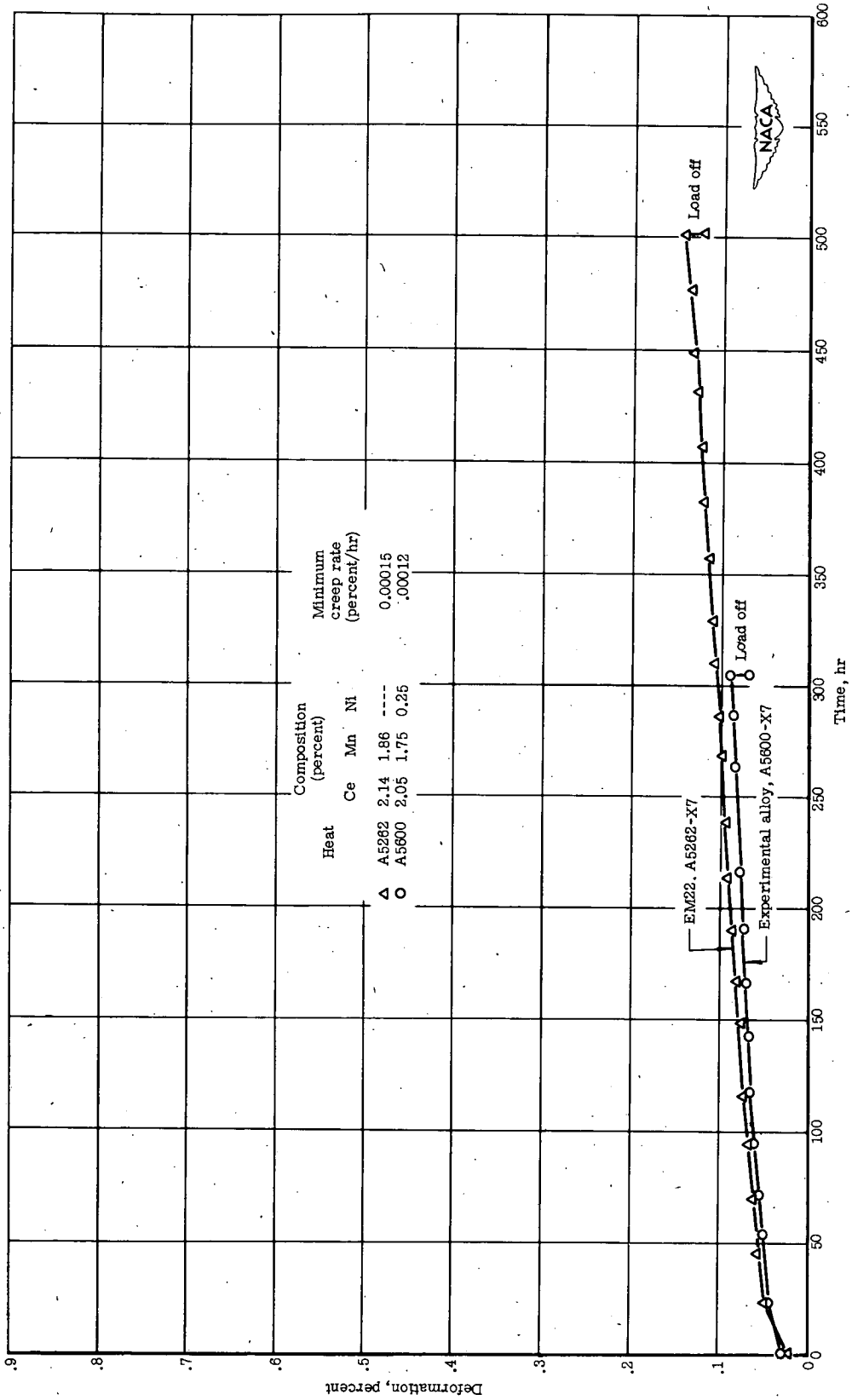
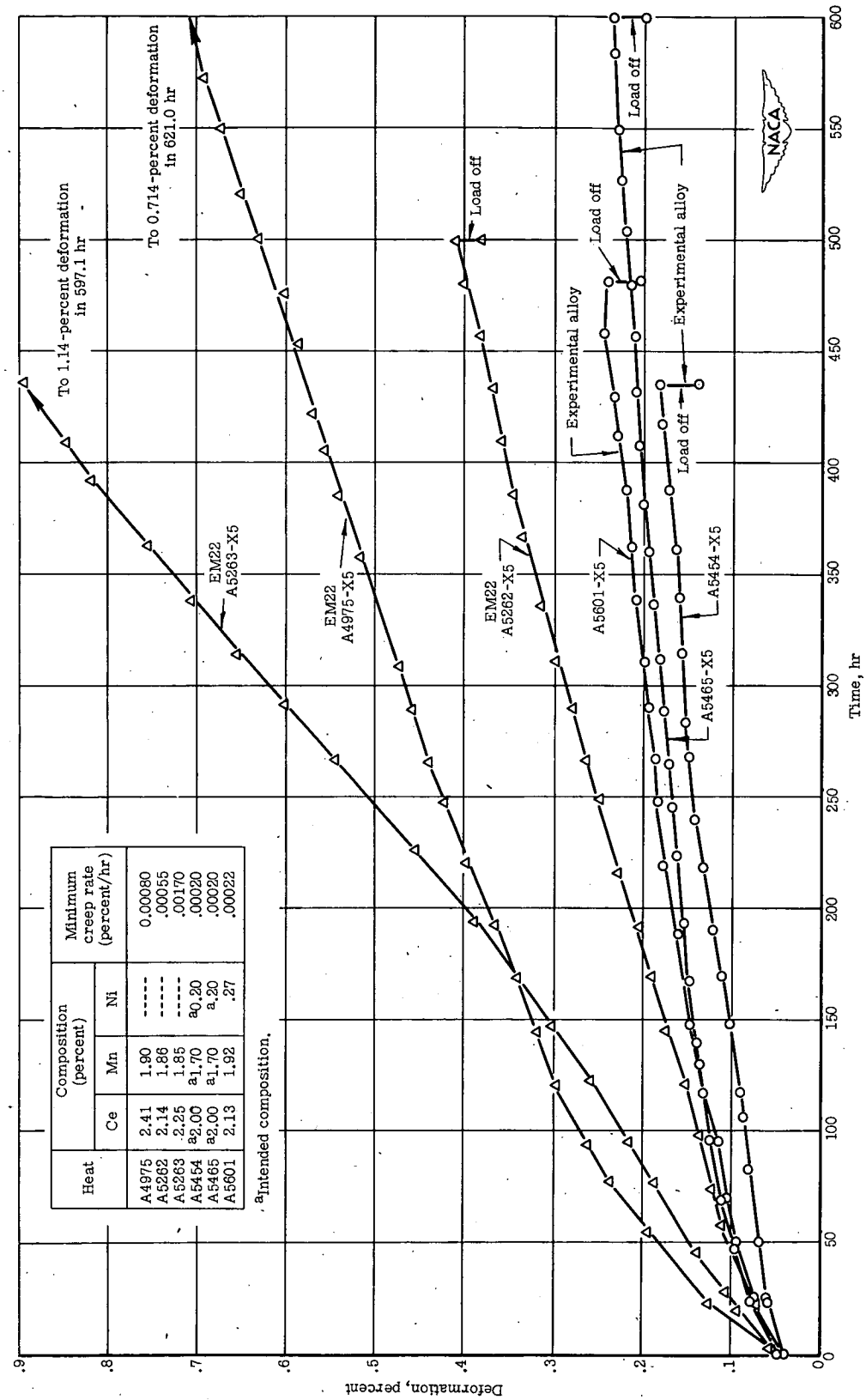


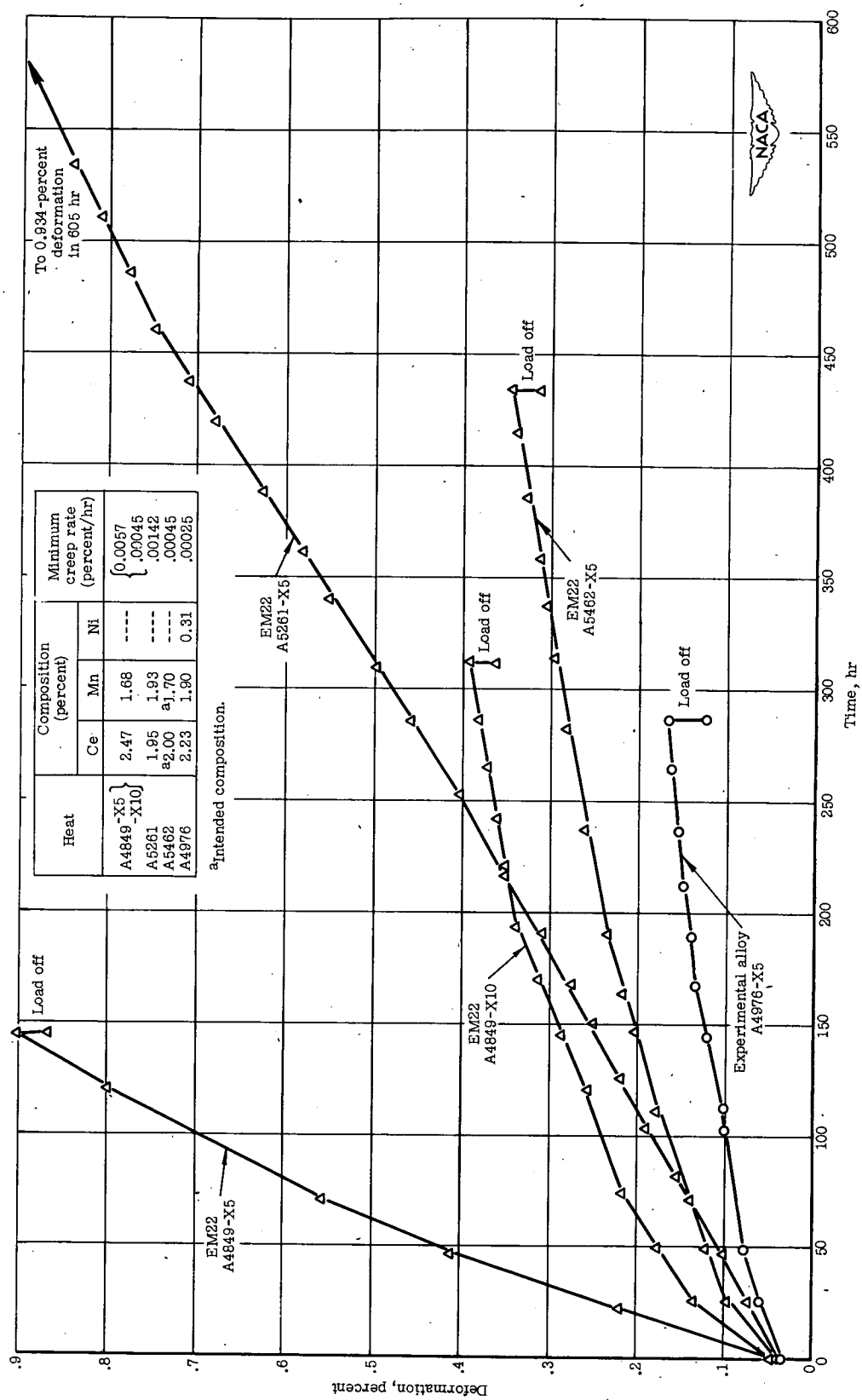
Figure 13.- Time-deformation curves of EM22 alloy and experimental alloy of optimum composition. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 1300-psi stress.



Heat	Composition (percent)			Minimum creep rate (percent/hr)
	Ce	Mn	Ni	
A4975	2.41	1.90	-----	0.00080
A5262	2.14	1.86	-----	.00055
A5263	2.25	1.85	-----	.00170
A5454	[a]2.00	[a]1.70	[a]0.20	.00020
A5465	[a]2.00	[a]1.70	[a].20	.00020
A5601	[a]2.13	1.92	.27	.00022

[a]Intended composition.

Figure 14.- Time-deformation curves of three heats of EM22 alloy and three heats of experimental alloy of optimum composition. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 2000-psi stress.



Heat	Composition (percent)			Minimum creep rate (percent/hr)
	Ce	Mn	Ni	
A4849-X5 -X10	2.47	1.68	----	0.0057 .00045
A5261	1.95	1.93	----	.00142
A5462	[a]2.00	[a]1.70	----	.00045
A4976	2.23	1.90	0.31	.00025

[a]Intended composition.

Figure 15.- Time-deformation curves of three heats of EM22 alloy and one heat of experimental alloy of optimum composition. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 2000-psi stress.

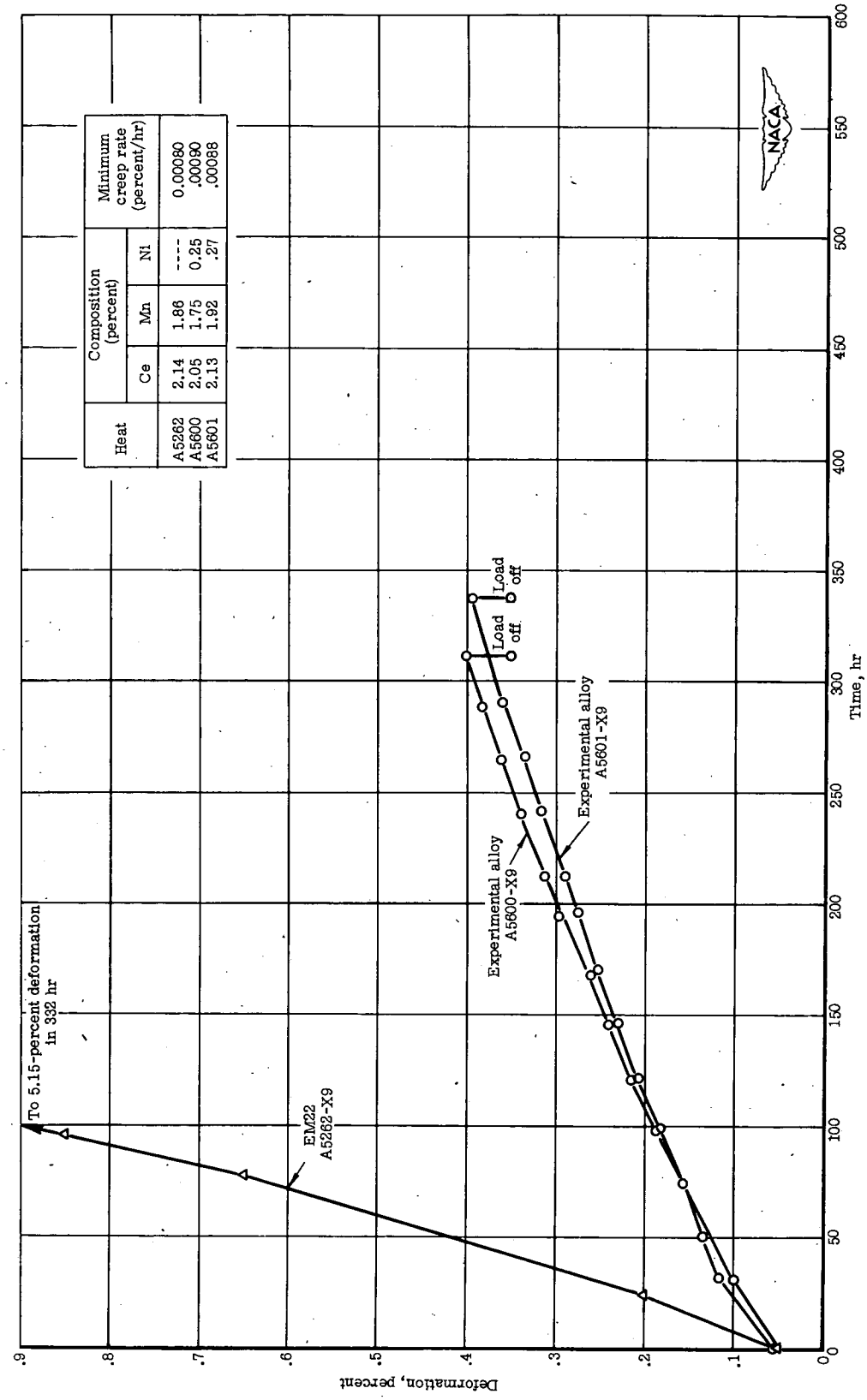


Figure 16.- Time-deformation curves of EM22 and experimental alloy of optimum composition. Specimens tested in heat-treated, aged, and stabilized condition at 600° F under a 2500-psi stress.

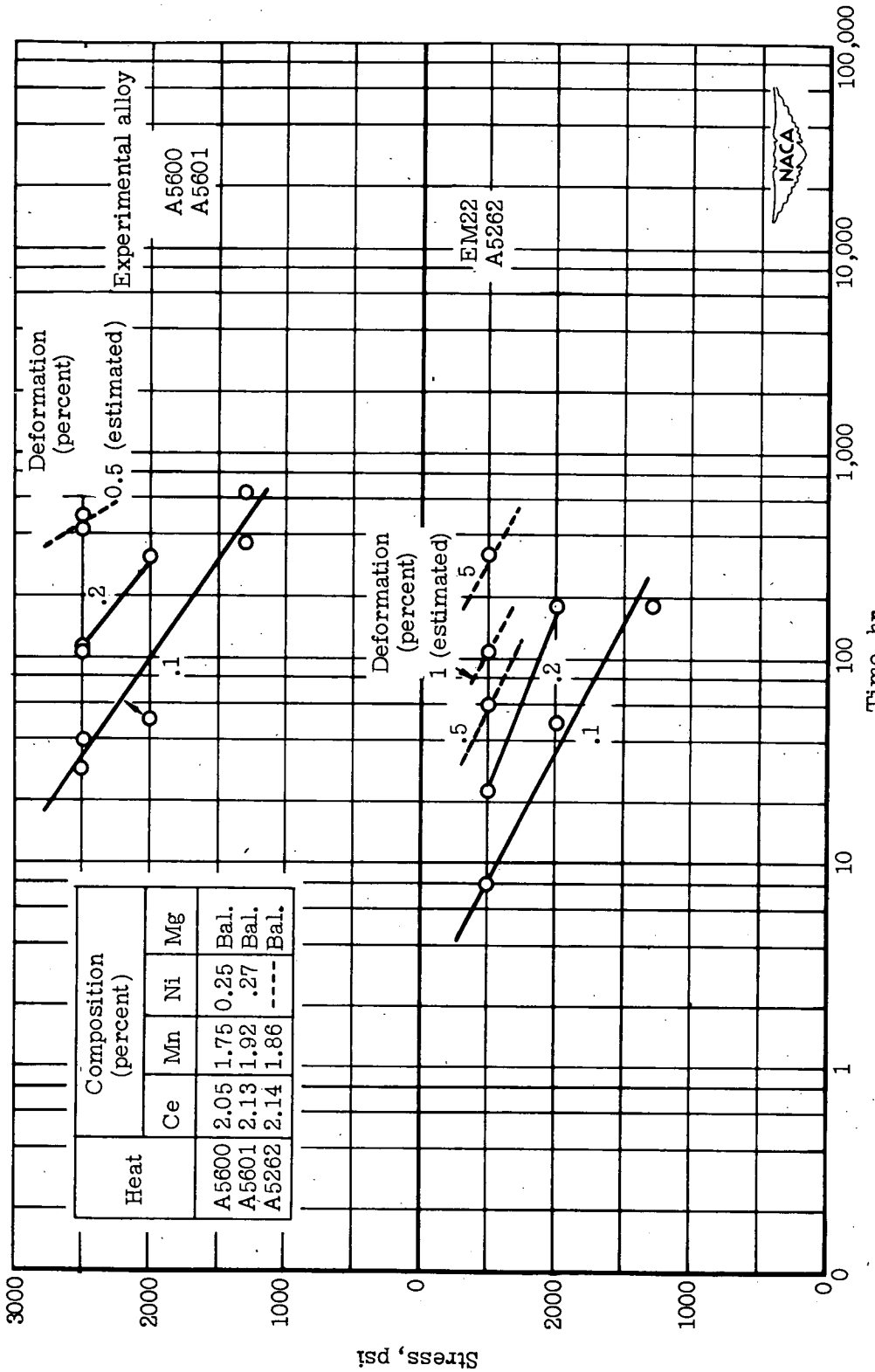


Figure 17.- Comparison of some design data on extruded EM22 and two heats of experimental alloy of optimum composition. Specimens tested in heat-treated, aged, and stabilized condition at 600° F.

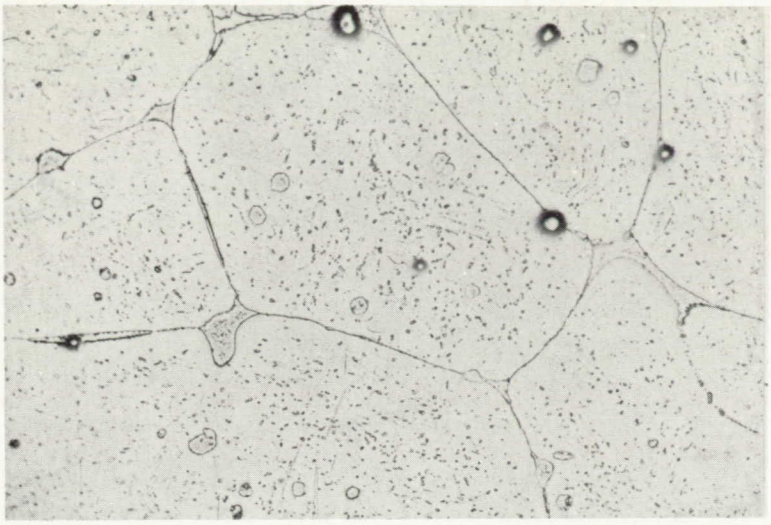


Figure 18.- Photomicrograph of experimental alloy of optimum composition (2.23 percent cerium, 1.90 percent manganese, and 0.31 percent nickel) in heat-treated, aged, and stabilized condition at a magnification of 250X. Heat, A4976-X5; heat-treating temperature, 1040° F; minimum creep rate at 600° F and a 2000-psi stress, 0.00025 percent per hour; deformation in 120 hours, 0.110 percent; duration of test, 287.0 hours; total deformation, 0.167 percent.

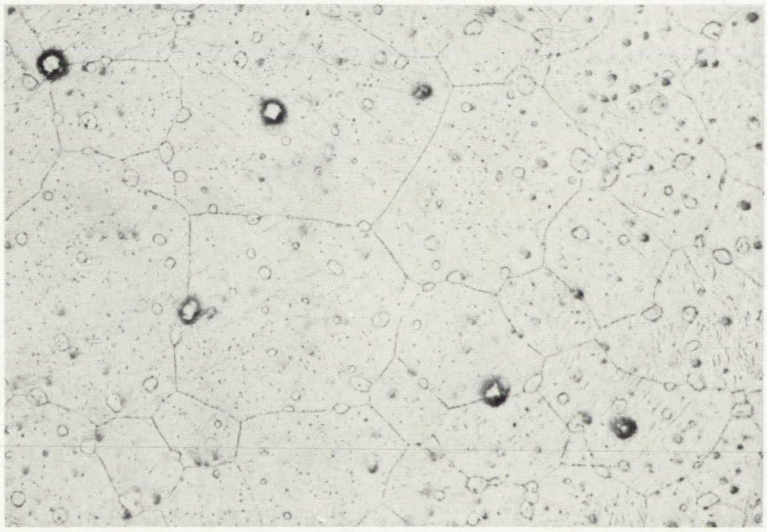


Figure 19.- Photomicrograph of experimental alloy of optimum composition (2.23 percent cerium, 1.90 percent manganese, and 0.31 percent nickel) in heat-treated, aged, and stabilized condition at a magnification of 250X. Heat, A4976-X7; heat-treating temperature, 1000° F; minimum creep rate at 600° F and a 2000-psi stress, 0.0015 percent per hour; deformation in 120 hours, 0.262 percent; duration of test, 284.3 hours; total deformation, 0.635 percent.

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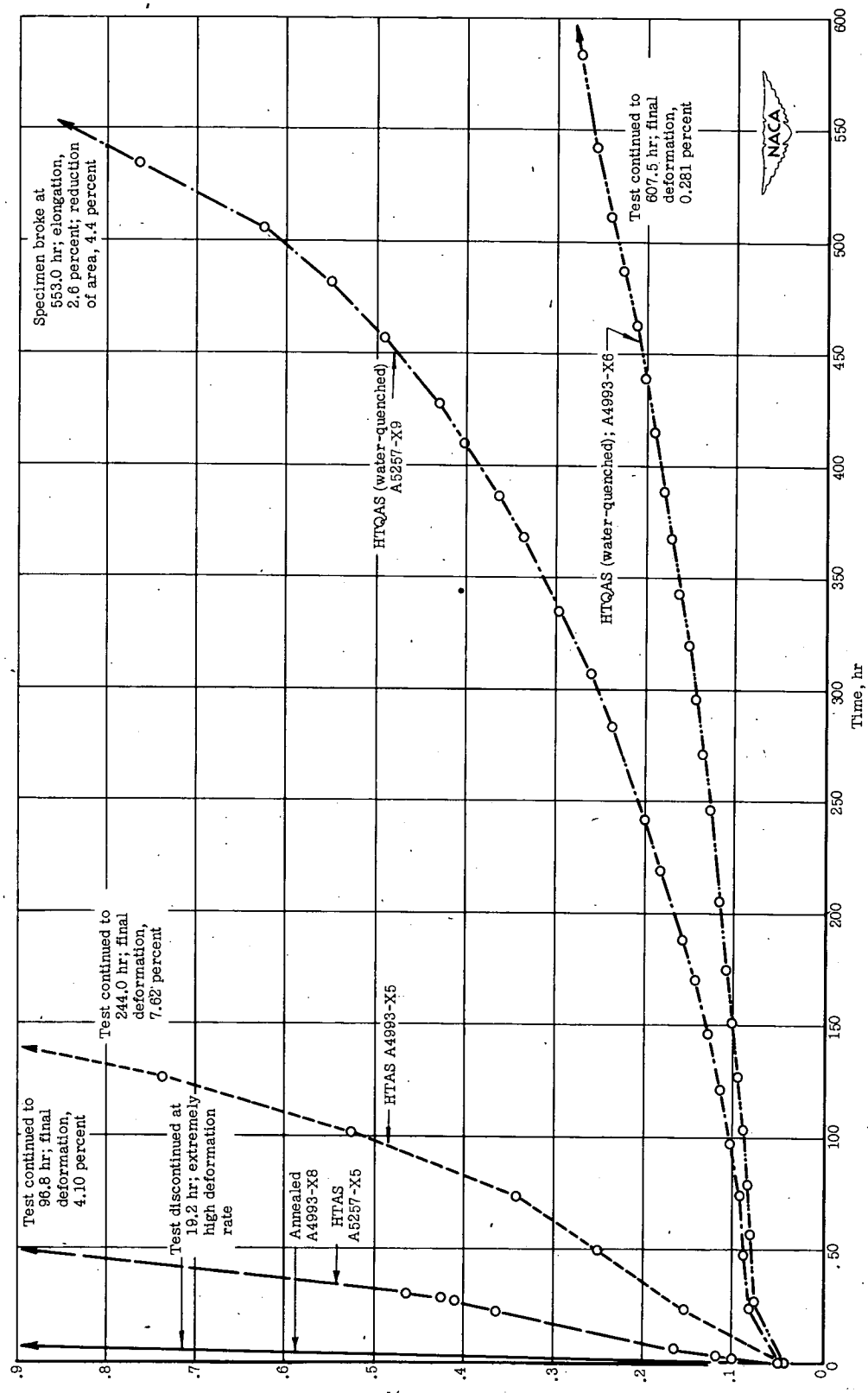

Figure 20.- Time-deformation curves showing effect of heat treatment of extruded M1 magnesium alloy. Specimens tested at 600° F under a 2000-psi stress.

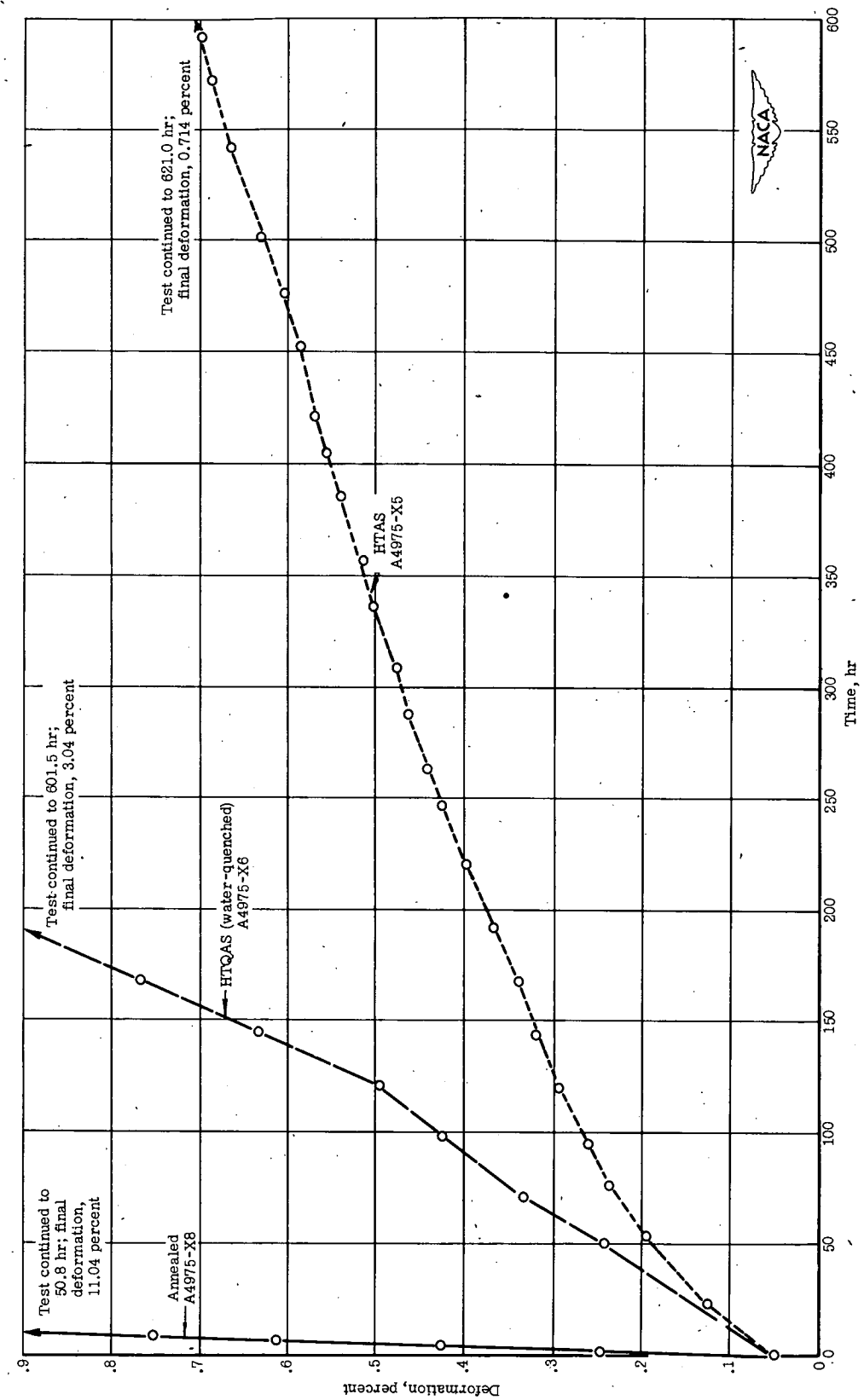

Figure 21.- Time-deformation curves showing effect of heat treatment of extruded EM22 alloy. Specimens tested at 600° F under a 2000-psi stress.

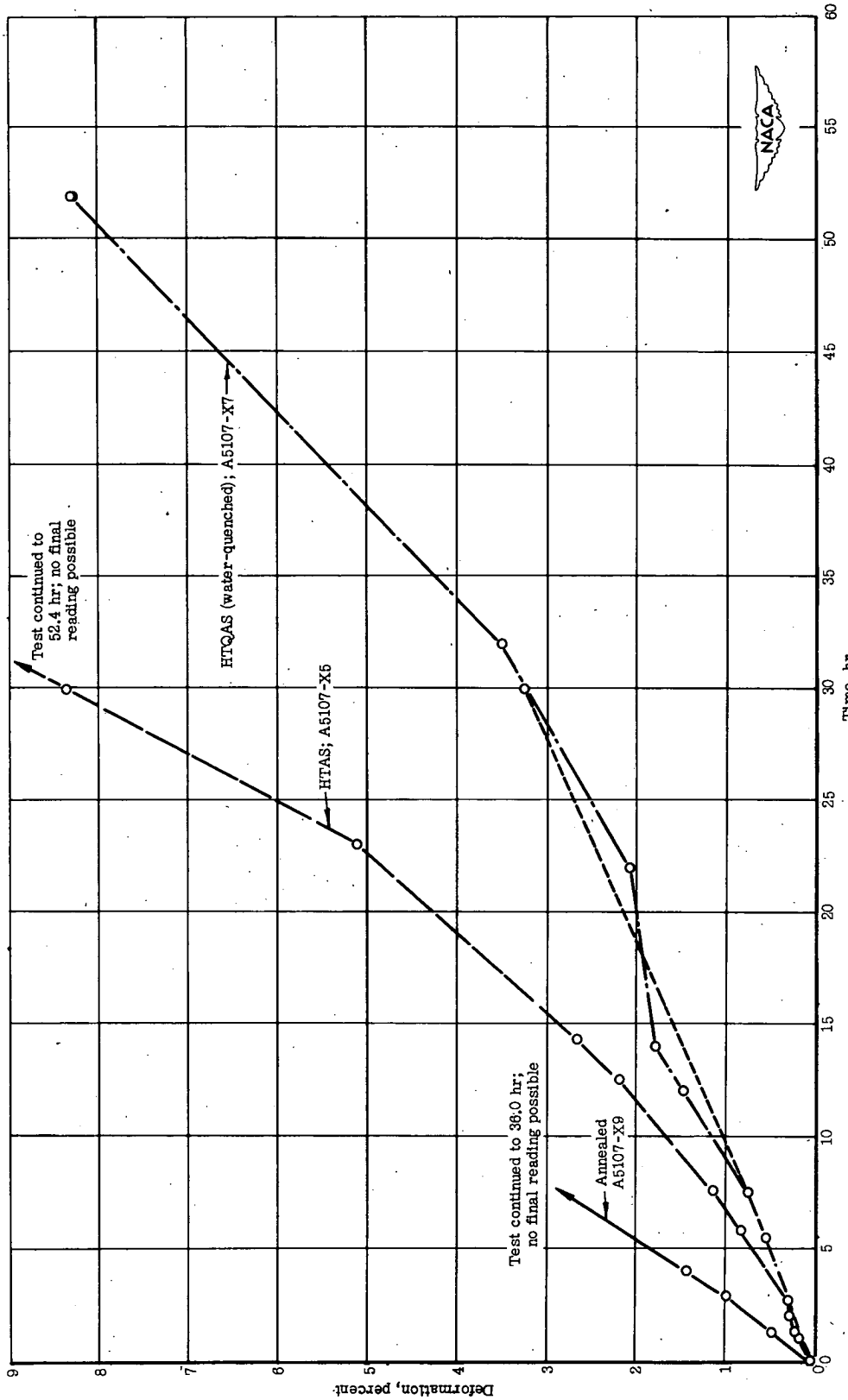

Figure 22.- Time-deformation curves showing effect of heat treatment on an extruded magnesium alloy containing 2.33 percent cerium and 0 percent manganese. Specimens tested at 600° F under a 2000-psi stress. (Note that a larger scale is used in this figure.)

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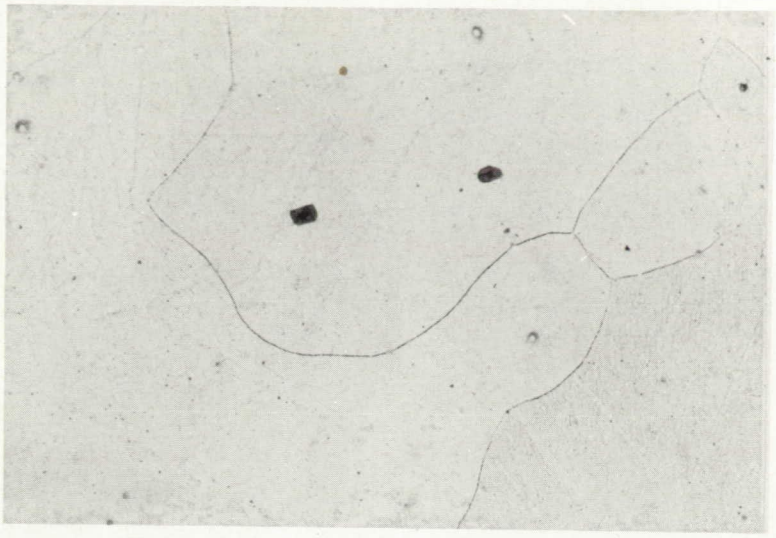

Figure 23.- Photomicrograph of M1 alloy (0 percent cerium and 1.80 percent manganese) in heat-treated, aged, and stabilized condition at a magnification of 250X. Heat, A4993-X5; minimum creep rate at 600° F and a 2000-psi stress, 0.0046 percent per hour; deformation in 120 hours, 0.680 percent; duration of test, 244 hours; final total deformation, 7.65 percent. (Shows a single phase - coarse grain. Manganese phase is not shown.)

Figure 24.- Photomicrograph of M1 alloy (0 percent cerium and 1.80 percent manganese) in heat-treated, quenched, aged, and stabilized condition at a magnification of 250X. Heat, A4993-X6; minimum creep rate at 600° F and a 2000-psi stress, 0.0003 percent per hour; deformation in 120 hours, 0.090 percent; duration of test, 607 hours; final total deformation, 0.281 percent. (Similar to fig. 23. The cause of better creep resistance is probably a finer distribution of the manganese phase, but this is not revealed by metallography up to 500X.)

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Figure 25.- Photomicrograph of an alloy containing 2.33 percent cerium and 0 percent manganese in heat-treated, aged, and stabilized condition at a magnification of 250X. Heat, A5107-X5; minimum creep rate at 600° F and a 2000-psi stress, very high; duration of test, 52 hours; final total deformation, 8.68 percent. (Shows equiaxed magnesium-rich grains and small particles of cerium-rich phase in a manganese-free alloy.)

Figure 26.- Photomicrograph of an alloy containing 2.33 percent cerium and 0 percent manganese in heat-treated, quenched, aged, and stabilized condition at a magnification of 250X. Heat, A5107-X7; minimum creep rate at 600° F and a 2000-psi stress, very high; duration of test, 52 hours; final total deformation, 8.32 percent. (Similar to fig. 25. Both specimens have very poor creep resistance. The quench has produced no noticeable effect.)

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Figure 27.- Photomicrograph of an alloy containing 1.34 percent cerium and 1.56 percent manganese in heat-treated, aged, and stabilized condition at a magnification of 250X. Heat, A5110-X5; minimum creep rate at 600° F and a 2000-psi stress, 0.0014 percent per hour; deformation in 120 hours, 0.303 percent; duration of test, 597 hours; final total deformation, 1.05 percent. (Shows small particles of cerium-rich phase.)

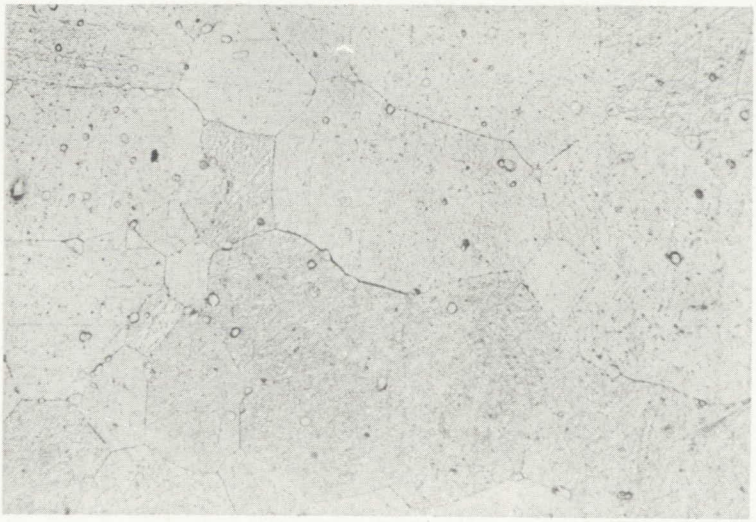

Figure 28.- Photomicrograph of an alloy containing 1.34 percent cerium and 1.56 percent manganese in heat-treated, quenched, aged, and stabilized condition at a magnification of 250X. Heat, A5110-X7; minimum creep rate at 600° F and a 2000-psi stress, 0.001 percent per hour; deformation in 120 hours, 0.375 percent; duration of test, 599 hours; final total deformation, 0.952 percent. (Similar to fig. 27. Fine structure within the grain is more pronounced. Creep properties are similar to those of specimen in fig. 27.)

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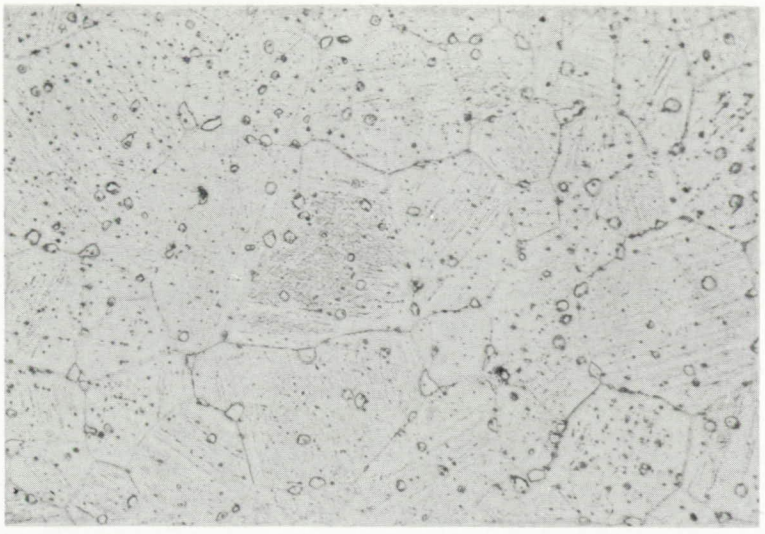

Figure 29.- Photomicrograph of an alloy containing 1.34 percent cerium and 1.56 percent manganese in annealed condition at a magnification of 250X. Heat, A5110-X9; minimum creep rate at 600° F and a 2000-psi stress, 0.057 percent per hour; deformation in 120 hours, 7.50 percent; duration of test, 152 hours; final total deformation, 9.92 percent. (Soluble material is precipitated; presumably the manganese-rich phase is also precipitated. Poor creep resistance.)

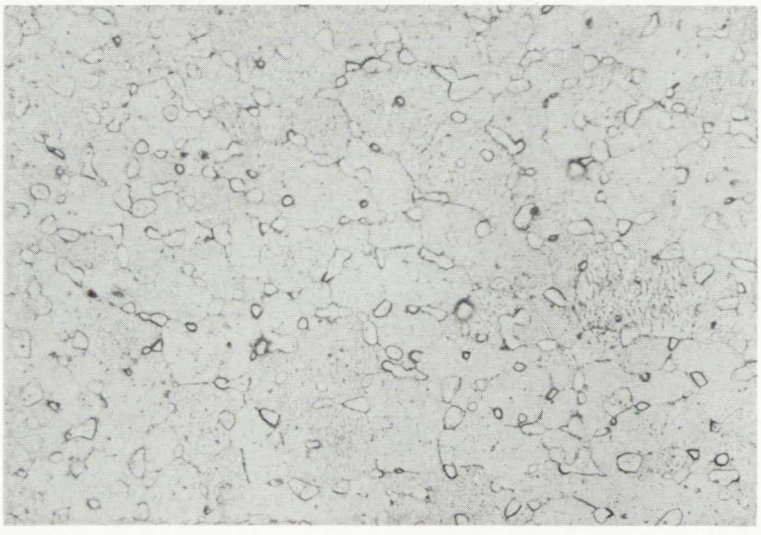

Figure 30.- Photomicrograph of EM62 alloy (6.01 percent cerium and 1.81 percent manganese) in heat-treated, aged, and stabilized condition at a magnification of 250X. Heat, A4973-X5; minimum creep rate at 600° F and a 2000-psi stress, 0.0020 percent per hour; deformation in 120 hours, 0.504 percent; duration of test, 360 hours; final total deformation, 1.53 percent. (Shows large amount of undissolved cerium-rich phase.)

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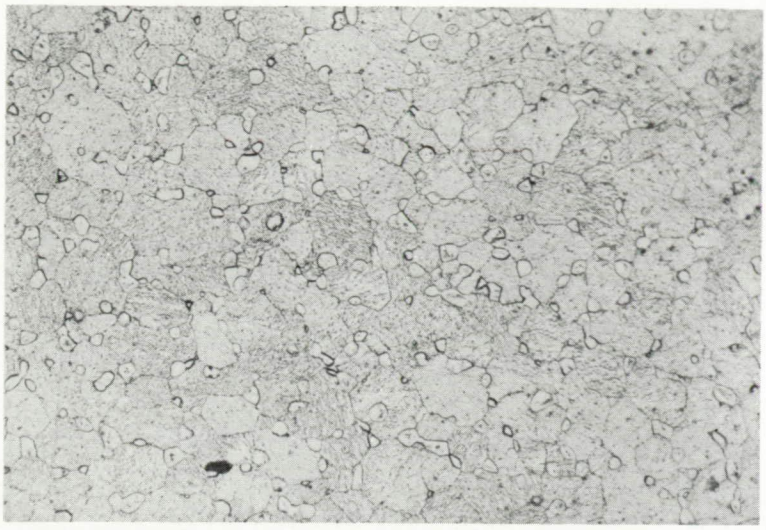

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Figure 31.- Photomicrograph of EM62 alloy (6.01 percent cerium and 1.81 percent manganese) in heat-treated, quenched, aged, and stabilized condition at a magnification of 250X. Heat, A4973-X6; minimum creep rate at 600° F and a 2000-psi stress, 0.00043 percent per hour; deformation in 120 hours, 0.230 percent; duration of test, 594 hours; final total deformation, 0.445 percent. (Similar to fig. 30. Fine structure is more pronounced. Creep resistance is better.)

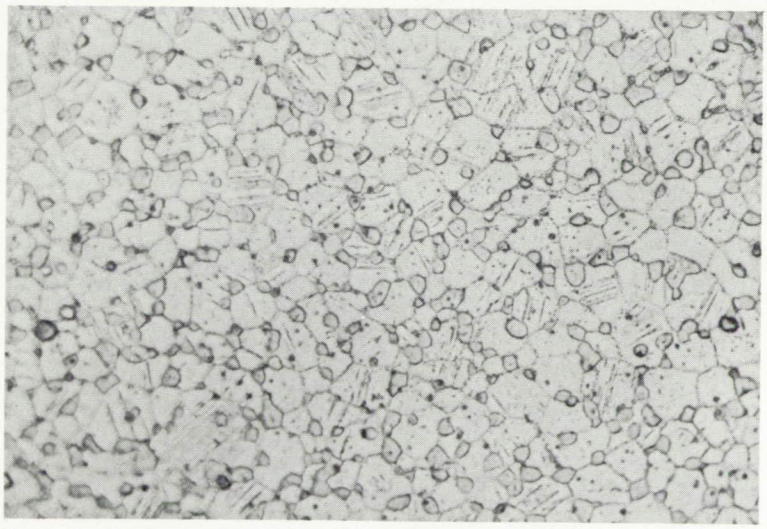

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Figure 32.- Photomicrograph of EM62 alloy (6.01 percent cerium and 1.81 percent manganese) in annealed condition at a magnification of 250X. Heat, A4973-X8; minimum creep rate at 600° F and a 2000-psi stress, 0.077 percent per hour; deformation in 120 hours, 9.00 percent; duration of test, 126 hours; final total deformation, 9.96 percent. (Presumably, the soluble phase indicating the manganese has coagulated. Poor resistance to creep.)

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Figure 33.- Electron micrographs of cast EM22 alloy (2.41 percent cerium and 1.90 percent manganese) in heat-treated, aged, and stabilized condition at a magnification of 5000X. Specimen, A4975-A1; minimum creep rate at 600° F and a 2000-psi stress, 0.00015 percent per hour; deformation in 120 hours, 0.080 percent; duration of test, 307 hours; final total deformation, 0.133 percent. (Sample was cut from unstressed portion of creep test specimen.)

Figure 34.- Electron micrographs of cast EM22 alloy (2.41 percent cerium and 1.90 percent manganese) in heat-treated, aged, and stabilized condition at a magnification of 5000X. Specimen, A4975-A1; minimum creep rate at 600° F and a 2000-psi stress, 0.00015 percent per hour; deformation in 120 hours, 0.080 percent; duration of test, 307 hours; final total deformation, 0.133 percent. (Sample was cut from stressed portion of creep test specimen.)

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Figure 35.- Electron micrographs of an extruded alloy containing 2.33 percent cerium and 0 percent manganese in heat-treated, aged, and stabilized condition at a magnification of 5000X. Specimen, A5107. (This sample was not tested in creep; it was used to establish a base line for comparison with the cerium-manganese alloys. Specimen A5107-X5, which was tested in creep, is a duplicate of this bar.)

Figure 36.- Electron micrographs of extruded EM22 alloy (2.41 percent cerium and 1.90 percent manganese) in annealed condition at a magnification of 5000X. Specimen, A4975-X8; minimum creep rate at 600° F and a 2000-psi stress, 0.175 percent per hour; duration of test, 51 hours; final total deformation, 11.04 percent. (Sample was taken from unstressed portion of creep test specimen.)

Figure 37.- Electron micrographs of extruded EM22 alloy (2.41 percent cerium and 1.90 percent manganese) in annealed condition at a magnification of 5000X. Specimen, A4975-X8; minimum creep rate at 600° F and a 2000-psi stress, 0.175 percent per hour; duration of test, 51 hours; final total deformation, 11.04 percent. (Sample was taken from stressed portion of creep test specimen.)

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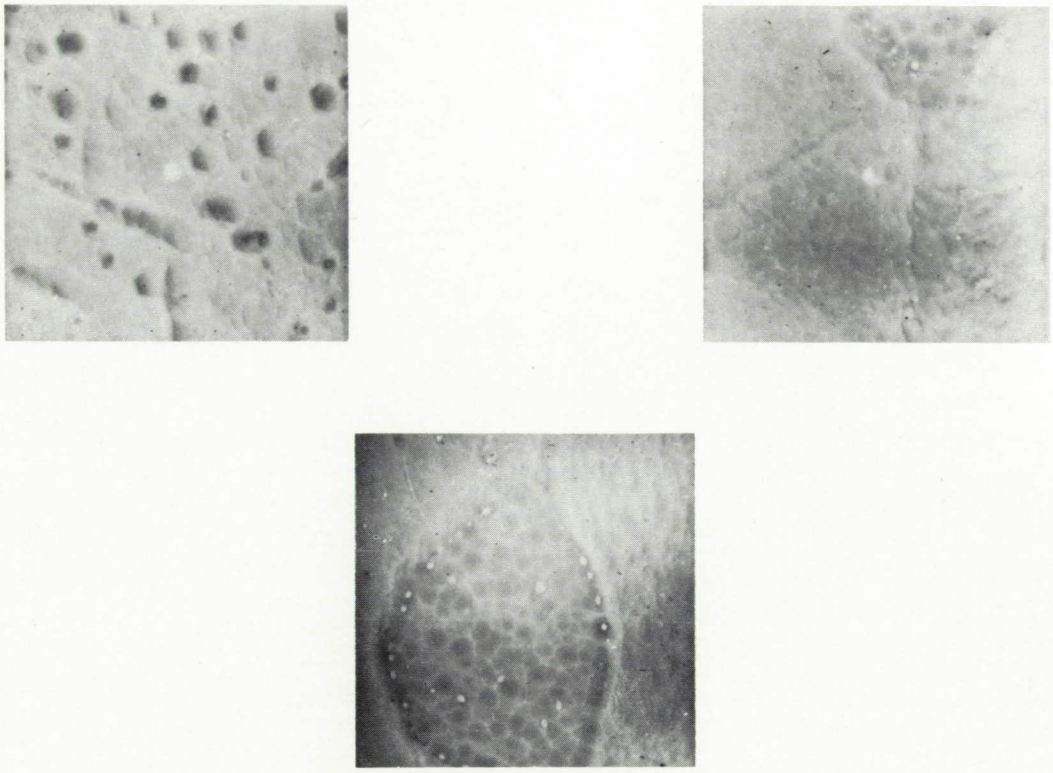

Figure 38.- Electron micrographs of extruded EM22 alloy (2.41 percent cerium and 1.90 percent manganese in annealed condition at a magnification of 5000X. Specimen, A4975-X8; minimum creep rate at 600° F and a 2000-psi stress, 0.175 percent per hour; duration of test, 51 hours; final total deformation, 11.04 percent. (Sample was taken from unstressed portion of creep test specimen. These micrographs are similar to those in fig. 36, except that they were taken from other fields.)

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